AD-750 617

THE PRINCETON PENNSYLVANIA ARMY AVIONICS RESEARCH PROGRAM. A FUNDAMENTAL STUDY OF STATIC ELECTRIC PHENOMENA (APPLIED TO HELICOPTERS)

G. J. Born, et al

Princeton University

Prepared for:

Army Electronics Command

March 1972

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

AD750617

AD

Research and Development Technical Report
ECOM-02412 - 10

THE PRINCETON PENNSYLVANIA ARMY AVIONICS RESEARCH PROGRAM

Final Task Report

A FUNDAMENTAL STUDY OF STATIC ELECTRIC PHENOMENA
(Applied to Helicopters)

by

G.J. Born
W.F. Burke
E.J. Durbin

March 1972

Contract DA28-043 AMC-02412 (E)
The Trustees of Princeton University
Princeton, New Jersey

DISTRIBUTION STATEMENT

This document is approved for public release; distribution unlimited.

ECOM

UNITED STATES ARMY ELECTRONICS COMMAND · FORT MONMOUTH, N.J.

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as a official Government indorsement or approval of commercial products or services referenced herein.

Disposition

Destroy this report when it is no longer needed. Do not return it to the originator.

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) The Trustees of Princeton University Princeton, New Jersey	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A Fundamental Study of Static Electric Phenomena (Applied to Helicopters)

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Final Task Report 1 September 1966 - 30 December 1971

5. AUTHOR(S) (First name, middle initial, last name)

G. J. Born
W. F. Burke
E. J. Durbin

6. REPORT DATE	7a. TOTAL NO OF PAGES	7b. NO OF REFS
March 1972	77	6

8a. CONTRACT OR GRANT NO DA 28-043 AMC-02412 (E) b. PROJECT NO 1H1 62202 A219 Task 07 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ECOM - 02412-10

10. DISTRIBUTION STATEMENT

This document is approved for public release; distribution unlimited

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Electronics Command Fort Monmouth, N. J. 07703 AMSEL-VL-D

13. ABSTRACT

This is the final report on the investigation of "A Fundamental Study of Static Electric Phenomena".

In this report is given a summary of the charging and discharging processes of a helicopter in flight. Emphasis is placed upon obtaining approximations for estimating the magnitude of the problem for given environmental conditions. The problems of electrostatic charging and discharging of helicopters with regard to safety of personnel, cargo and radio frequency interference are stated. Acceptable safety limits for personnel protection and safe cargo handling are presented.

A solution to the cargo hook up problems of electrostatic charged helicopters is proposed, using current technology.

A summary is given of the construction and test results of this "safe-cargo hook up system" (SAFCAR).

The Appendixes summarizes work on corona discharges, space charges, and environmental effects on charging and discharging phenomena.

DD FORM 1473

Security Classification

Security Classification

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
static electricity						
helicopter electrostatic discharger						

Security Classification

Research and Development Technical Report

ECOM - 02412-10

THE PRINCETON PENNSYLVANIA ARMY AVIONICS RESEARCH PROGRAM

Final Task Report

A FUNDAMENTAL STUDY OF STATIC ELECTRIC PHENOMENA (Applied to Helicopters)

by

G. J. Born
W. F. Burke
E. J. Durbin

March 1972

Contract DA28-043 AMC-02412 (E)
The Trustees of Princeton University
Princeton, New Jersey

DISTRIBUTION STATEMENT

This document is approved for public release; distrubution unlimited

United States Army Electronics Command · Fort Monmouth, N. J.

Reports Control Symbol
OSD - 1366

Technical Report ECOM - 02412-10 March 1972

THE PRINCETON PENNSYLVANIA ARMY AVIONICS RESEARCH PROGRAM

Final Task Report

A FUNDAMENTAL STUDY OF STATIC ELECTRIC PHENOMENA
(Applied to Helicopters)

Contract No. DA 28-043 AMC-02412 (E)

DA Project No. 1H1 62202 A219 Task 07

Prepared by

G. J. Born
W. F Burke
E. J. Durbin

For

U. S. Army Electronics Command, Fort Monmouth, New Jersey

DISTRIBUTION STATEMENT

This document is approved for public release; distribution unlimited

ABSTRACT

This is the final report on the investigation of "A Fundamental Study of Static Electric Phenomena".

In this report is given a summary of the charging and discharging processes of a helicopter in flight. Emphasis is placed upon obtaining approximations for estimating the magnitude of the problem for given environmental conditions. The problems of electrostatic charging and discharging of helicopters with regard to safety of personnel, cargo and radio frequency interference are stated. Acceptable safety limits for personnel protection and safe cargo handling are presented.

A solution to the cargo hook up problems of electrostatic charged helicopters is proposed, using current technology.

A summary is given of the construction and test results of this "safe-cargo hook up system" (SAFCAR).

The Appendices summarizes work on corona discharges, space charges, and environmental effects on charging and discharging phenomena.

FOREWORD

The work reported herein has been performed by Princeton University under the Princeton Pennsylvania Army Avionics Research (PPAAR) Program. The work was supported under Contract DA 28-043 AMC-02412 (E), DA Project # 1H1 62202 A219, Avionics Technology: Task 07, Avionics Techniques Studies.

This is the final report on A Fundamental Study of Static Electric Phenomena.

Contributors to the work reported herein but not listed as authors are:

R. Creed	USAECOM
M. M. Chrepta	USAECOM
H. E. Inslerman	USAECOM
E. G. Sharkoff	Picatinny Arsenal

The contributors to this work and authors often worked together as a team for the test set up, the testing and evaluating test results. The development of the SAFCAR system is the result of an excellent team work between the Avionics Laboratory, US Army Electronics Command and the Instrumentation and Control Laboratory of Princeton University. Part of the appendixes are extracted from the dissertation of Willard F. Burke, Princeton University, to be published.

One of the results of this work is a simple inexpensive solution to the electrostatic problems during helicopter cargo hook up operation. This safe cargo hook up system or SAFCAR has been tested successfully on a cargo helicopter and over a wide range of environmental conditions. When in the design of new cargo helicopters emphasis is placed upon a possible solution of electrostatic problems, the safe cargo hook up system can be implemented with relatively small penalties in cost and weight.

It is hoped that the results of the research pursued under this program will provide the basis for further developments by the Avionics Laboratory of the U. S. Army Electronics Command.

The Instrumentation and Control Laboratory of Princeton University acknowledges the understanding encouragement and constructive criticism provided by members of the Avionics Laboratory.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

C_H	= the capacitance of the aircraft in farads
I_C	= the charging current in amperes
Q	= the net charge in coulombs
R_g	= the ground resistance, or the resistance from the ground contact to earth ground
R_H	= the effective helicopter resistance to ground
R_s	= the safe cargo handling resistance
t	= the time in seconds
V_A	= atmospheric potential in volts
V_H	= the voltage in volts
$V_{H\infty}$	= helicopter potential for $t \to \infty$

LIST OF SYMBOLS USED IN APPENDIX A1

A	= area
A_o	= area, A, at $t = t_o$, $s = s_o$
$\bar{A}_s$	= tube volume
$\bar{A}_o$	= $\bar{A}$ at $t = t_o$, $s = s_o$
A_1, A_2	= areas
A_o	= constant
A_1, A_2	= constants
a	= coordinate, r, of ion departure
a	= radius of wire and sphere sources
B_o	= constant in formula for threshold
B_1, B_2	= constants
b	= coordinate at which ions reach b
C	= constant
C_1, C_2, C^1	= constants
d	= separation from ground
E	= electric field
E_a	= E at a
E_b	= E at b
$E_o(0,r)$	= threshold field
$f_{(j)}$	= mole fraction of gas molecule of type (j)
H	= % humidity/100; $(0 < H < 1)$
i	= current
i_e/i_1	= electron relative current
i_n/i_1	= negative ion relative current
i_p/i_1	= positive ion relative current
i_o	= constant with units of current
$(i)_V$	= current at constant voltage
$(i)_{V-V_o}$	= current at constant $V-V_o$
i_a, i_b	= currents of ions of type a, b
i_p	= positive ion current
i_1	= arbitrary normalizing constant with units of current
Δi	= abs(i_1-i_r)

$\bar{J}$	= current density
j, j'	= indices
K	= constant
k_o, k'_o, k_1, k'	= constants
$k^{(i)}_{(j)(k)}$	= mobility of ion of type (i) in gas of type (j) mixed with gas of type (k)
k	= index
L	= length
m	= mass
$N_{(j)}$	= number density of ion of type (j)
n	= number density
$\bar{n}$	= unit normal vector
p	= pressure
p_o	= one atmosphere
p_{O_2}	= partial pressure of O_2 in gas mixture
p_w	= vapor pressure
$Q^{N_2^+}_{O_2}$	= momentum transfer cross section for collisions of nitrogen ions with oxygen molecules
q	= charge
R	= resistance V/i
r	= displacement in field direction
r_t	= tube radius
r_c	= value of r where corona avalanche begins
$S_G^{(V)_i}$	= $(\Delta(V)_i/(V)_i)/(\Delta G/G)$
$\bar{s}$	= displacement along path of tube of flux
s_c	= effective separation from c.c.
s_o	= s when field is first predominantly current-dependent
T	= temperature (^oK)
T_o	= standard temperature
t	= needle thickness
t	= time
t_o	= time at t s = s_o

V	= gap voltage
V_c	= corona threshold voltage
$V(r)$	= corona voltage
V_a	= voltage at r = a
$(V)_i$	= voltage at constant current
$\bar{v}_d$	= mean ion drift velocity due to field
$v_{therm_{O_2}}$	= thermal velocity of O_2 molecules
v_{r_t}	= dr_t/dt
w	= wind velocity
x_1, x_2	= variables in differential equation
y_1, y_2	= variables in differential equation
α	= gas polarizability, first Townsend Coefficients
γ	= efficiency of
δ	= ρ/ρ_o
ϵ_i	= ionization potential
λ	= charge per unit length
η	= attachment coefficient
μ	= mobility
μ_o	= mobility at ntp
$\nu_{O_2}^{N_2^+}$	= collision frequency of nitrogen ions with oxygen
ρ	= gas mass density
ρ_o	= ρ at ntp
ρ_c	= charge density
$\bar{\rho}$	= average ρ
τ	= transit time
Φ	= work function

I. INTRODUCTION

One of the problems in electrostatics is the electrostatic charging and discharging phenomena experienced by helicopter in flight.

In forward flight, the presence of static charges on the airframe presents no particular operational problems. It is quite possible that some radio and navigational equipment interference may be experienced during natural corona discharge, but passive dischargers can diminish these effects.

A cargo helicopter is required to hover in the vicinity of ground personnel and equipment during external cargo loading and unloading operations under various tactical environmental conditions. Under certain adverse environmental conditions, large electrostatic potentials on the airframe can present a serious hazard.

The problem can be divided into three basic areas: first, injury to ground handling personnel performing the cargo hook-up; second, possible damage to the cargo itself as a result of discharge current passing through it; third, premature detonation of external armament systems, ignition of fuel air mixtures in the vicinity of the arcs produced when ground contact is made.

In this report a summary is given of the charging and discharging processes of an airborne helicopter. Emphasis is placed upon obtaining such approximations that the magnitude of the problem can be estimated for a given helicopter under certain environmental conditions.

In Chapter II are summarized the charging and discharging phenomena of airborne helicopters namely; the electrical properties of the helicopter in the atmosphere, the charging and discharging processes and the potential accumulation of a helicopter in flight. The problems and safety limits of a charged helicopter with regard to safety of personnel, cargo and radio frequency interference are stated in Chapter III. In Chapter IV are presented the observations that lead to the conclusion of proposing a grounding technique as a practical solution to the cargo hook up problems of electrostatically charged helicopters.

The system description is given in Chapter V and a summary of system tests and evaluation is presented in Chapter VI. Parts of the Appendix I are extracted from the dissertation of Willard Burke, Princeton University (to be published) Reference 1. The appendix summarizes the fundamentals of corona discharges and the sensitivity to environmental changes.

Evaluation of test results and acceptable safety limits, for personnel and cargo suggest the requirements for discharging a hovering cargo helicopter.

The requirements for a reasonable solution to the discharge of a hovering cargo helicopter are:

1. A discharge capability that discharges the helicopter from several hundred kilovolts potential to approximately earth potential, and/or limits the discharge current, at the point of contact, to a safe level.

2. A steady discharge current capability, under all environmental conditions, of at least 100 to 200 micro amperes. (Magnitudes of Corona discharge currents are strongly influenced by environmental effects.)

3. A discharge time constant of the order of a second (tentative, subject to results of further investigation).

4. The method should be reasonable in cost and weight. An interim method using current technology that satisfies these requirements is the Safe Cargo Hook Up System which is described in this report.

II. THE ELECTROSTATIC CHARGING AND DISCHARGING PHENOMENA OF AIRBORNE HELICOPTERS

The main elements involved in the electrical charging and discharging phenomena of airborne helicopters are:

A. The electrical properties of the helicopter in the atmosphere.

B. The charging and discharging processes.

C. The potential accumulation of a helicopter in flight.

A. The Electrical Properties of the Helicopter in the Atmosphere

The capacitance of the helicopter at high altitudes (infinite atmosphere) depends on the helicopter shape and dimensions.

In proximity of the ground, the helicopter capacitance is increased to the sum of the infinite atmosphere capacitance and the capacitance of the helicopter to ground.

In Figure 1 measurements are given of the helicopter capacitance C_H, which is approximately proportional to helicopter body dimensions.

The resistance of the air is inversely proportional to the concentration of charge carriers (electrons whether or not attached to molecules, and ions), the charge on them, and their mobility. The mobility of the

charge carriers is inversely proportional to the air density. Under certain atmospheric conditions such as smoke and fog, charge carriers attach themselves to impurities thereby forming "large ions" with reduced mobility. In the lower atmosphere the mobility and ion concentration depend upon the purity of the air; this explains the large variations in measured air resistance. At sea level, the atmospheric resistivity is in the order of 1×10^{13} to $x\ 10^{14}$ ohms/meter. The resistivity of the air in the vicinity of a propeller or rotor system is decreased over that of still air because the propeller or rotor system imparts velocity to the air, and the effective mobility of the ions is increased. Since the resistivity is a function of both the number of ions and their mobility, the effect of this velocity is to reduce resistivity (order of $1 \times 10^{13}\,\Omega$ per meter).

The effective helicopter resistance is defined as the electrical resistance in ohms of the airborne helicopter to ground. The effective resistance of a helicopter, with the engine running, is in the order of 5×10^{9} ohms.

Figure 2 shows the measurements of effective helicopter resistance, as a function of altitude and corona discharge current.

The combined effect of helicopter capacitance and effective resistance determines the helicopter charge and discharge time constant, which is in the order of 10 seconds. Measured values of a few seconds to 30 seconds have been recorded, depending on helicopter size, hover height, and atmospheric conditions.

B. The Charging and Discharging Processes

When the processes described below increase or decrease the absolute potential of the helicopter with respect to the earth's potential, they are called, respectively, charging or discharging processes.

1. Atmospheric Electric Field Charging Processes. A helicopter flying in the atmosphere, in the absence of all other charging processes, will assume a potential equal to the atmospheric potential which exists at that altitude. The atmospheric potential near the ground at an altitude h, is in the order of the product of altitude and potential gradient. In fair weather, the potential gradient is usually positive and can be in the order of several hundred volts per meter. In electrically disturbed weather, fog or rain for example, the potential gradient is usually negative and can be in the order of several kilovolts per meter. Under conditions of an approaching thunderstorm, much higher potential gradients have been measured, on the order of a thousand kilovolts per meter prior to lightning strikes. Figure 3 shows expected field strengths under various atmospheric conditions.

2. Nonatmospheric Field Charging Processes. Many effects have been described and measured. The most important ones that yield high charging currents are described as follows:

Triboelectric Charging. Triboelectric or frictional charging results when dissimilar materials come in contact with one another. When particles normally found in a helicopter environment, such as dust, sand, snow, rain, etc., strike the helicopter, the aircraft charges. The charge rate or current depends upon the materials, mass, total surface area of particles intercepted. On the average, these currents are less than 50 microamperes, but under extreme conditions, currents of several times this number have been reported (References 1,2). Some evidence exists that the effective helicopter resistance is lowered in conditions of high triboelectric charging (R_H in the order of 5×10^8 ohms).

Precipitation. Heavy rain, especially from cumulonimbus clouds, snow, etc., can be charged and produce positive or negative charging currents in the order of 100 microamperes, although maximum currents reported in heavy rainstorms near Singapore have been as high as 0.5 mA.

The self-generating charging process. The main source reported for the self-generating charging process is the engine, which can produce ions for one predominant polarity. Also, the ions generated are probably a function of fuel and air composition, as well as engine condition. The aircraft is charged to the opposite polarity of the ions. The order of magnitude of current reported for engine exhaust is in the order of a few microamperes (Reference 2). Although current levels in excess of 10 microamperes have been reported.

The nonatmospheric charging processes are functions of the amount of particles intercepted. This is a function of helicopter weight, density of the particles in the air and type of particles. In Figure 4, a monogram is given of the charging current as a function of environment and helicopter weight. This graph can be used to estimate the charging current for a given helicopter weight and environment; examples are given for the UH1 and the CH47 helicopters.

3. Corona Discharge Process. The basic mechanism of a corona discharge consists of electrons accelerated by the strong electric field around any sharp point. The field strength around the sharp point is directly proportional to the potential at the point and inversely proportional to the radius of curvature of the point. Thus, when the radius is very small (sharp point) the field strength can be quite large. Locally accelerated electrons ionize the air; these ions (space charge) are removed from the vicinity of the point by the motion of the air or by the electrical field.

The magnitudes of the Corona current from a point is proportional to the voltage squared and is strongly dependent upon geometry and atmospheric conditions. Also, the Corona current increased with air velocity. When there are Corona currents in the vicinity of the helicopter, the effective helicopter resistance to ground is decreased.

C. The Potential Accumulation of a Helicopter in Flight

The airborne helicopter can become charged by any of the charging processes. In principle, these charging processes can be divided into two groups:

1. Electric Field Charging Processes

Assume that an uncharged helicopter becomes airborne. The uncharged helicopter has a capacitance C_H with respect to earth. The value of the helicopter capacitance is a function of altitude. When the atmospheric potential that exists at the helicopter altitude is not equal to ground potential, then the helicopter starts charging toward the atmospheric potential. In the absence of all other charging processes, the helicopter potential V_H will become equal to the atmospheric potential V_A. The time constant of this atmospheric charging process is equal to the product of $R_H \times C_H$ (in order of 10 to 30 seconds).

2. Charging Current Processes

When only a charging current is present in absence of an electric field charging process, the potential ofthe helicopter rises to a value of

$$V_H = \frac{Q}{C_H} = \frac{\int I_C dt}{C_H} \qquad (1)$$

where V_H is the voltage in volts

Q is the net charge in coulombs

C_H is the capacitance of the aircraft in farads

I_C is the charging current in amperes

t is the time in seconds

In principle there is no limit on the helicopter potential V_H, but when the helicopter potential V_H rises sufficiently above or below atmospheric potential (V_A) that exists at the helicopter altitude, the corona discharge process starts. This is mainly corona current from sharp points. The helicopter discharge current increases as the potential rises, until a state of equilibrium is reached such that the charging current equals the discharging current. Figure 6 shows measured helicopter discharge current of the helicopter potential under natural conditions at 25 ft. hover altitude. The net effect of all the corona points on the airplane gives a total effective resistance R_H of the helicopter. This discharge rate is normally slower than the charge rates of the triboelectric, precipitation, and self-generating charging processes (few seconds or less).

The increase in helicopter potential above the atmospheric potential, due to the charging current I_C, is then equal to the product of the charging I_C and the effective helicopter resistance R_H.

The total helicopter potential V_H with resnect to ground is the sum of the atmospheric potential V_A and the voltage due to the charging current $R_H\ I_c$.

As described previously, the important elements in charging and discharging processes are:

a. The helicopter capacitance C_H (in the order of 10^{-9} F).

b. The effective helicopter air resistance R_H (in the order of 5×10^9 ohms).

c. The atmospheric potential V_A (the product of estimated potential gradient and helicopter height).

d. The charging current I_c (estimated from helicopter weight and environment).

The helicopter charging process can be modelled by the equivalent circuit as shown in Figure 5.

V_A is a voltage source or generator representing the atmospheric potential, I_c is the charging current of a current source or generator representing other charging mechanisms such as precipitation, blowing sand and dust triboelectric, etc., C_H is the capacitance between the helicopter and ground, and R_H is the resistance between the helicopter and ground. It should be noted that R_H in series with the voltage source V_A forms the real generator representing the effect of the earth's electric field and therefore R_H is also the internal resistance of this atmospheric voltage. V_H is the resultant voltage between the helicopter and ground due to the various sources. The helicopter resistance R_H is a function of the charging current I_c; for simplicity it is assumed that the R_H is a constant.

III. PROBLEMS AND SAFETY LIMITS OF A CHARGED HELICOPTER

If the helicopter capacitance is charged to a high voltage and discharges through personnel or cargo, hazardous conditions can occur. A large number of "safe" limits for discharges have been determined and reported in the literature. The problem can be divided into three parts, personnel safety, cargo safety, and radio frequency interference.

A. Personnel Safety - For a capacitor type of discharge through the human body (resistance on the order of a hundred to several thousand ohms), the sensation threshold level is an energy of the order of one (1) millijoule. (Note: 1 millijoule in 1×10^{-9} F, the helicopter capacity, corresponds to 1400V). Experience has shown that one can feel the effects of a 10 millijoule discharge under most circumstances. Note the level of energy discharged after a person scuffs across a rug in winter and touches some grounded object is typically 10 to 25 millijoules. It is felt that the sensation associated with a 10 millijoule discharge during the concentrated effort required to hook a sling load onto a

helicopter hook would be unnoticeable under most circumstances. The criterion used here is to prevent any discharge to a person which would cause him to move involuntarily as a reaction to the shock in such a manner that the loading operation would be aborted or the loader would fall down, lose his balance, or otherwise create a condition where he could be injured through falling.

On this basis, the 10 millijoule level was established as providing significant reduction in the shocking potential of an aircraft during loading and unloading operations. For a continuous current type discharge through the human body, the sensation threshold level is in the order of 1 mA. Due to the relatively short discharge time, the peak current is higher in the capacitance discharge for the same sensation. Laboratory and field tests have confirmed that when a high resistance is placed in series with the human body, the discharge time of a capacitor increases and the threshold level is then higher than the continuous current sensation threshold which is the order 1 mA. This observation can be the basis of a solution to the personnel safety problem using the 1 mA current sensation threshold level.

E. Cargo Safety - Some examples of published safety limits of a capactive type of discharge for cargo operations are as follows:

1. Explosives (commerical initiators): 10^{-3} millijoule

2. Explosives (secondary): several millijoules to 0.5 joule

3. Ignition of fuel-air-gas mixtures:

   For stoichiometric mixtures: 0.5 - 1 millijoule.

   Published safety limits for electrical currents are:

   (a) 180-200 μa for constant corona current,

   (b) 1 ma for a duration of 100 millisec, $\{\text{or } i^2\, t \cong 10^{-7}\}$

   (c) 100 ma for a duration of 0.01 millisec.

Normally in open air, the probability of having a stochiometric mixture appears to be small. Under these circumstances, larger energies are required to ignite the fuel air mixture. In all the helicopter loading and unloading operations to date, there have been few if any cases where ammunition or fuel has been ignited or exploded due to static electricity discharges. On this basis alone, the probability for discharge of significant amounts of energy through sensitive portions of ammunition appear to be small, and the probability of igniting fuel is equally small. This experience, of course, has been with helicopters unprotected from the electrostatic charge accumulation. Any reduction in the charge on the helicopter which can be discharged to ground during loading or unloading operations would certainly reduce the probability of ignition.

C. Radio Frequency Interference - When the helicopter is charged to a high potential, erratic corona discharges occur which produce RFI. This electrical noise source can severely hinder and even saturate some communication and navigation equipment.

IV. THE SAFE CARGO HOOK UP SYSTEM

General Description: The Safe Cargo Hook Up System is intended to provide personnel safety during the cargo hook up procedure, and should be considered as a solution until a better method becomes available.

Considering the hazards of electrically charged helicopters during cargo hook up procedures, the following observations should be made:

1. Properly, grounding the helicopter (by an electrical conductor) and keeping the helicopter grounded solves the personnel problem.

2. Almost any continuous contact between a conductor and ground surface (sand, asphalt, grass) is sufficient to bring the potentials to safe levels.

3. During the grounding procedures before ground contact is made, personnel on the ground may come in contact with the "grounding conductor". Upon making ground contact, under certain conditions, the discharge energy can ignite fuel-air mixtures and explosives.

4. The continuous direct current level threshold of sensation is in the order of one miliampere. The effects of short durations of direct current, such as capacitance resistance discharges, are less severe than the effects of continuous direct currents of the same peak level.

5. When the discharge occurs via a resistive path, the current in the discharge path is determined by the helicopter potential and the resistance of the path.

<u>The Combination of These Observations Leads to the Following Conclusions:</u>

The best method to date, to discharge a hovering cargo helicopter under all conditions, is a proper grounding technique. All aircraft should be grounded and continuously held at ground potential when fuel, explosives, or similar dangerous cargo are loaded or unloaded. For ground personnel safety and when fuel-air mixtures are present, it is advisable that the first earth contact be made via a resistive path, with a resistance on the order of 100 megohms.

When a system is designed according to these conclusions, it can be modelled as shown in Figure 5.

A. Safe Cargo Hook Up System Analysis

The elements in the figure left of the marking "helicopter voltage" V_H represent the helicopter charging process. The elements to the right of V_H represent the cargo handling, in particular:

R_s is the safe cargo handling resistance (100 megohms).

R_g is the ground resistance, or the resistance from the ground contact to earth ground ($\leq$ 8 megohms).

The resistance of the man, or electrical conduction path, is R_m.

When electrical contact is not made through the resistances R_s, R_m and R_g, then the helicopter voltage is determined by:

$$C_H \frac{dV_H}{dt} + \frac{V_H - V_A}{R_H} - I_c = 0 \tag{2}$$

With the initial condition $V_H = 0$ at $t = 0$

this yields:

$$V_H = (V_A + R_H I_c)(1 - e^{\frac{-t}{R_H C_H}}) \tag{3}$$

The charging time constant is:

$$T = R_H C_H \tag{4}$$

and the final helicopter potential at equilibrium is:

$$V_H = V_A + R_H I_c \tag{5}$$

Note that if the helicopter air resistance R_H can be made zero (or small) then the helicopter potential V_H equals (or approximates) the atmospheric potential V_A.

When electrical contact is made and an electrical conduction path is established through the resistances R_s, R_m and R_g, then the helicopter potential is determined by:

$$C_H \frac{dV_H}{dt} + \frac{V_H - V_A}{R_H} + \frac{V_H}{R_s + R_m + R_g} - I_c = 0 \tag{6}$$

For the initial conditions $V_H = V_{HO}$ at $t = 0$, this yields for the helicopter voltage V_H:

$$V_H = \frac{(R_s + R_m + R_g)}{R_H + (R_s + R_m + R_g)} (V_A + I_c R_H)(1 - e^{-\frac{t}{C_H R}}) + V_{HO}\, e^{-\frac{t}{C_H R}} \tag{7}$$

where: R is the parallel combination of R_H and the grounding path

$$R = \frac{R_H (R_s + R_m + R_g)}{R_H + (R_s + R_m + R_g)}$$

The final helicopter potential at equilibrium is:

$$V_{H\infty} = \frac{(R_s + R_m + R_g)}{R_H + (R_s + R_m + R_g)} (V_A + I_c R_H) \tag{8}$$

The discharge time constant is

$$T_d = C_H R \tag{9}$$

The current through the ground contact is

$$I = \frac{V_H}{R_s + R_m + R_g} \tag{10}$$

B. Special Cases of the Safe Cargo Hook Up System Analysis

1. No Ground Resistance ($R_g = 0$) and No Safe Cargo Resistance ($R_s = 0$)

This is the case of the unprotected helicopter and a man or grounding device with resistance R_m making the electrical conductive path between helicopter and ground. Under normal operational conditions, the electrical resistance R_m is much smaller than the helicopter air resistance R_H.

Substitution of $R_s = 0$, $R_g = 0$ and $R_m << R_H$ yields:

$$R = \frac{R_m R_H}{R_H + R_m} \doteq R_m$$

$$V_H \doteq (V_A + R_H I_c) e^{-\frac{t}{R_m C}}$$

The current I through the conduction path is:

$$I = \frac{V_H}{R_m} \tag{10a}$$

This current given by equation 10a will be passed through the ground contact or man touching the charged helicopter and under normal operating conditions exceeds by far the "safe current level". By placing the safe cargo resistance R_s in series with the man resistance (R_m), the current level can be kept within "safe current levels".

For example: if a helicopter of 1,000 μμF is charged to 100 kilovolts and the resistance R_m = 500 ohms, the peak current equals 200 amperes in the impulse discharge of 5 joules (compare this with the safety limit).

2. No Ground Resistance ($R_g = 0$) and a Safe Cargo Resistance

$R_g \doteq 10^8$ Ohms

When making ground contact, such a discharge system should have the following characteristics:

a. Peak discharge current in the order of 1 milliampere (sensation threshold for personnel). For example: when a helicopter is charged to 100 kilovolts, the discharge current is

$$\frac{100 \times 10^3 \text{ volts}}{100 \times 10^6 \text{ ohms}} = 1 \times 10^{-3} \text{ ampere}$$

b. The discharge time constant less than a second. The discharge time constant equals the helicopter capacitance times the total resistance to ground, which is always less than the lowest resistance path to ground. For example: a helicopter of 10^{-9} farads has a time constant of

$$T = C_H(R_S + R_m) \doteq C_H R_S = 10^{-9} \times 10^8 = 10^{-1} \text{ seconds}$$
$$(R_m << R_S)$$

c. The final helicopter potential at equilibrium will be $V_{H\infty}$

$$V_{H\infty} = \frac{R_S + R_m}{R_H + R_S + R_m}(V_A + I_c R_H) \doteq \frac{R_S}{R_H + R_S}(V_A + I_c R_H)$$

For example: assume a helicopter operating under rain conditions hovering at ≐ 30 feet, an atmospheric potential gradient of −4kv/m, a triboelectrical charging current of − 30 μA, an effective air resistance of 2×10^9 ohms.

The helicopter potential before ground contact is made is:

$$V_H = (V_A + I_c R_H) = (-40 + -60) = -100 \text{ kilovolts}$$

The final helicopter potential after ground contact is made is:

$$V_{H\infty} \doteq \frac{R_S}{R_H + R_S}(V_A + I_c R_H) = \frac{10^8}{2.1 \times 10^9} 10^5 = -4.8 \text{ kilovolts}$$

This voltage on a helicopter of 1,000 picofarads is capable of energy discharge equal to $1 \times 10^{-9} \times (4.8 \times 10^3)^2$ = 22 milijoules.

3. A Ground Resistance R_g and a Safe Cargo Resistance R_s

Under normal operating conditions, such as over clay, sand, runway surfaces, the measured ground resistance R_g is less than the safe cargo resistance R_s (10^8 ohms) and the effect of the ground resistance is small. However, there can exist situations where the ground resistance R_g is large. This might occur over a thick layer of fresh snow.

When the safe cargo hook up system is used as designed, and no other contact with the helicopter is made (then in series with the safe cargo handling resistor), then no problem exists as the current through the conduction path is less than with no ground resistance. Hence: when the safe cargo resistance is placed in series with the hook and only hook contact is made, electrical current limiting is effective and a ground resistance R_g has no serious effects on the safe cargo hook up system.

However, the final helicopter potential after the ground contact is made equals:

$$V_{H\infty} \doteq \frac{R_s + R_g}{R_H + R_s + R_g} (V_A + I_c R_H)$$

For example: a helicopter charged to -100 kv, and a ground resistance of $R_g = 5 \times 10^8$ ohms, the final helicopter voltage becomes

$$V_{H\infty} = \frac{10^8 + 5 \times 10^8}{2 \times 10^9 + 10^8 + 5 \times 10^8} 10^5 = -23 \text{ kilovolts}$$

In case personnel should come in contact with the helicopter still charged to a potential $V_{H\infty}$, two situations can occur:

a. Personnel is on a place that has also a large ground resistance R_g. In this case, an energy discharge or charge occurs which is equal to $\frac{1}{2} C_{man} V_H^2$. For this example $E = \frac{1}{2} C_{man} V_H^2 = \frac{1}{2} 50 \times 10^{-12} \times (23 \times 10^3)^2 =$ 13 millijoules.

b. Personnel is standing on a large load with a capacitance, e.g. truck, etc. By making contact with the helicopter, the safe cargo hook up resistance is short circuited. This short circuit provides then the discharge path for charge equalization between charged helicopter capacitance and uncharged load capacitance.

For example, if the load capacitance was also 1,000 pf, the energy transfer through the short circuit can be $\frac{1}{2}\ \frac{1}{2} C_H V_{H\infty}^2$ = 130 millijoules, which is a serious shock hazard.

Hence, when in extreme cases the ground resistance is large, personnel should only come in contact with a protected cargo hook and should not come in contact with the helicopter.

V. SYSTEM DESCRIPTION

Various construction methods can be used to provide for a resistive element in the electrical discharge path when ground contact is made. The construction of these devices can be simplified considerably when the electrical potential on the helicopter is limited; for example, by the use of passive dissipators.

Passive dissipators on the rotor blades diminish the potential build up on the helicopter. Properly designed passive dischargers (corona points) reduce the effective helicopter resistance. In Figure 7, curves 1, 2, and 3 represent passive dischargers on the rotor blades of the CH47. Curve 4 is obtained by placing a passive dissipator (braiding) 100 feet below the helicopter. (NOTE: 40 microamperes discharge current, with 26 kilovolts on the CH47 helicopter, yielding an effective helicopter resistance of only 6.5 x 10^8 ohms.) For the CH54 helicopter or any other cargo hook up helicopter which lowers the cargo hook, one can use a passive dissipator on the cargo hook. This can reduce the electrostatic problems considerably when sufficient cable length is used during the hook up. There is evidence that when the surface of helicopter rotor blades is electrically conductive and electrical contact is made with the helicopter fuselage, the electrostatic problem is reduced. (For example, compare Figure 6, curve 3 and Figure 7, curve 1.)

A resistive element can be placed between the cargo hook and the airframe (SAFCAR System) or can be placed in the grounding path (resistive grounding link). Both methods are described below:

A. An Electrical Resistive Element Between Cargo Hook and Airframe.

This element performs two functions:

a. It diminishes the electrical current through the cargo hook. This function provides a safe cargo hook up operation. When the maximum current through the cargo hook is limited to less than one milliampere (threshold of sensation), no electrical shock is experienced. The electrical current is determined only by the ratio of the potential difference and electrical resistance in the path: this is independent of a good ground contact.

b. After ground contact has been made, it reduces the helicopter potential with respect to ground.

The construction method for an insulated hook can be one of the following:

1. An Insulated Beam or Cargo Hook (resistance between airframe or cargo hook). This approach is operationally very desirable as cargo loading procedures are not affected. To use this method, a change in existing aircraft construction must be made; namely: (see following page)

CH47 helicopter: Replace the cargo beam with an insulated cargo beam. The cargo hook remains essentially unchanged except for wider rollers which are exchangeable with the standard hook. A prototype of this construction was made and performed successfully when tested.

CH54 helicopter: Change the hook construciton. This is a more involved task due to the small dimensions of the present hook.

2. Insulated Cargo Link. In this case, the resistance is placed between a new hook and the original cargo hook on the aircraft. In this approach, a "doughnut" type device with a hook is hung on the original cargo hook of the helicopter. The new hook does not need to be equipped with the safety devices of the helicopter cargo hook as in emergencies, the helicopter cargo hook provides these necessary devices. However, the new hook must have a spring restrained lever to prevent the cargo from slipping off the hook. This approach requires that a new cargo link be placed on the cargo hook by the personnel in the aircraft.

In the implementation of these methods, the cargo hook capacitance should be minimized because the cargo hook capacitance can cause an electrical charge transfer when hook contact is made. (Typical measured capacitance values of a CH47 cargo hook, $\leq$ 30 ppF).

B. An Electrical Resistive Element in the Grounding Path (grounding link)

The grounding link is a device that can be attached to the cargo hook or cargo and provides grounding with resistance in the grounding path. The purpose of a resistive grounding link is to reduce electrical potential of the helicopter and/or cargo to ground potential. The resistance diminishes the electrical current in the ground path when the grounding link comes in contact with ground, personnel or cargo.

Essentially, a ground link is a conductor of 8 feet or more in length with a resistance on the order of 10^8 ohms This length insures that ground contact is made before personnel can make contact with the hook. The grounding link reduces the helicopter potential to a value given by Equation (8).

In order to provide safety under all conditions, it is essential that a good ground contact ($R_g \leq 10^7$ ohms) is made and that the helicopter and load are grounded and kept grounded during cargo operations.

This method is the least expensive and can solve the personnel safety problem but requires changes in operational hook up procedures.

If desirable, as for flammable cargo, the grounding link can also be used for discharging the cargo prior to release. A "ground link" is then connected to the cargo so as to make ground contact before cargo release.

VI. SYSTEM TESTS AND EVALUATION

Laboratory tests were performed to confirm the current threshold levels with high voltages using resistors and small capacitances for simulating the hook capacitance to ground. It was assumed that passive dissipators in a helicopter would limit the helicopter voltage to the order of 100 kilovolts.

Several resistive grounding links were designed and tested in the laboratory. The test results were promising and a safe cargo hook up system was designed to insulate the cargo hook from the airframe of the CH47 helicopter by 100 kV. This beam, with its associated end caps, will accept the existing cargo hook with the modification of the additional four (4) rollers mounted on the increased length of roller pins. The hydraulic tubing and electrical connections have been worked out.

A static mechanical load test was performed at Earle Naval Ammunition depot. A 30-ton crane was rigged with spreader bars, and loads of 10 tons and 8 tons were lifted. First the 10-ton load was raised and held for 15 minutes. Two tons were removed from the test load, and the 8-ton load was raised and lowered at the maximum speed. The time for one cycle (pickup and drop) was 4 seconds. This was repeated 350 times. No visible damage nor indents were observed at the conclusion of this test.

The beam was tested electrically up to 100 kV and was measured to be 10^8 ohms. The touch test was performed in the ETD high-voltage lab. A ground strap was wrapped around the little finger and touch was made at 10 kV steps up to 70 kV. A mild sensation was detected at 30 kV on up to 70 kV. The second touch test was made up to 100 kV with the same results except that at 85 to 100 kV no sensation was experienced. In both tests a faint snap was heard just prior to touch.

The safe cargo hook up system (SAFCAR) was installed in a CH47 helicopter. The latter was artificially charged to 70 kV (limit of the voltage generator) The cargo hook was touched by personnel. The worst sensation detected, caused by the unprotected hook capacitance, corresponded to the mild shock one gets from a carpet. Similar experiments were conducted with resistive grounding links on a CH54 helicopter. A summary of the results is given in Figure 8.

The left ordinate axis gives the helicopter potential <u>with respect to ground</u>; the right ordinate axis gives the helicopter potential with respect to the potential of the atmosphere which exists at the helicopter altitude. The difference between the two ordinates is the atmospheric potential which is equal to potential gradient times helicopter altitude. In Figure 8, this atmospheric potential is 20 kilovolts. The passive dischargers on the rotor blades reduce the electrical helicopter potential with respect to the atmospheric potential which exists at the helicopter altitude.

The curve marked "safe cargo hook up system" (SAFCAR), or resistive grounding link, indicates the potential on the helicopter with respect to ground after electrical ground is made. With the safe cargo hook up system, the current is greatly reduced whenever electrical contact is made with the hook. When electrical ground contact is made and maintained, the helicopter cargo and hook potential become as indicated in Figure 8.

In the case of a resistive grounding link, Figure 8 indicates a lowering of the electrical potential (with respect to ground) of the helicopter and cargo hook when electrical ground contact is made and maintained.

The evaluation of the proposed systems can be summarized as follows:

1. Laboratory models of the "safe cargo hook up system" (SAFCAR) have been successfully tested in the laboratory and with artificially charged airborne helicopters.

2. The method is reasonable in cost and weight. Depending upon the system version chosen, no changes or only small changes need to be made in the operational cargo loading procedures.

3. If desirable, as for flammable cargo, a "grounding link" can also be used for discharging the cargo prior to release.

VII. RECOMMENDATIONS

A solution to the electrostatic problems connected with the loading of a hovering helicopter is proposed. The "safe cargo hook up system", which uses current technology, provides reasonable personnel and cargo safety during cargo hook up operations.

Some engineering problems should be further investigated and complete prototypes should be made to be tested in the field under all operational conditions.

In development or design of new cargo helicopters, emphasis should be placed upon the possible solutions of electrostatic problems.

The "safe cargo hook up system", if implemented in the basic helicopter design, could be incorporated with relatively small penalties in cost and weight.

REFERENCES

1. Burke, W.F., Air Velocity Measurement with the Ion Beam of the Positive Corona Discharge (PhD Dissertation to be published).

2. J. Seibert, Helicopter Static Electricity Measurement, TRECOM AD No. 282 087.

3. M.E. Rogers, and E.B. Miniham, Interim Report on Investigation of Static Build-Up on Helicopters with Particular References to Whirlwind MK10.s., Royal Aircraft Establishment Technical Report No. 66152

4. CH47 Cargo Helicopter, Cargo Beam Insulator Design and Evolution, Avionics Laboratory November 1968.

5. Sharkoff, E.G., Electrostatic Research, The Princeton Pennsylvania Army Avionics Research Program, 1969 3rd Annual Report, Report No. 5 Contract No. DA28-043 AMC-02412(E), DA Project No. 1H1 62202 A219 Task 07.

6. G.J. Born, E.J. Durbin, A Fundamental Study of Static Electric Phenomena, The Princeton Pennsylvania Army Avionics Research Program, 1970 4th Annual Report, Report No. 6, Contract No. DA28-043 AMC-02412(E), DA Project No. 1H1 62202 A219 Task 07.

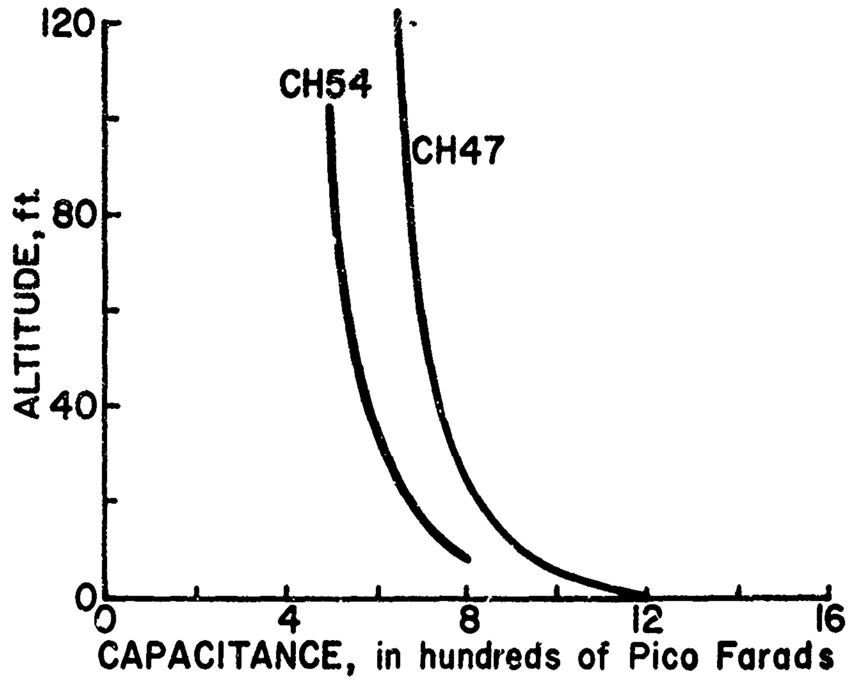


FIGURE 1. HELICOPTER CAPACITANCE AS A FUNCTION OF ALTITUDE

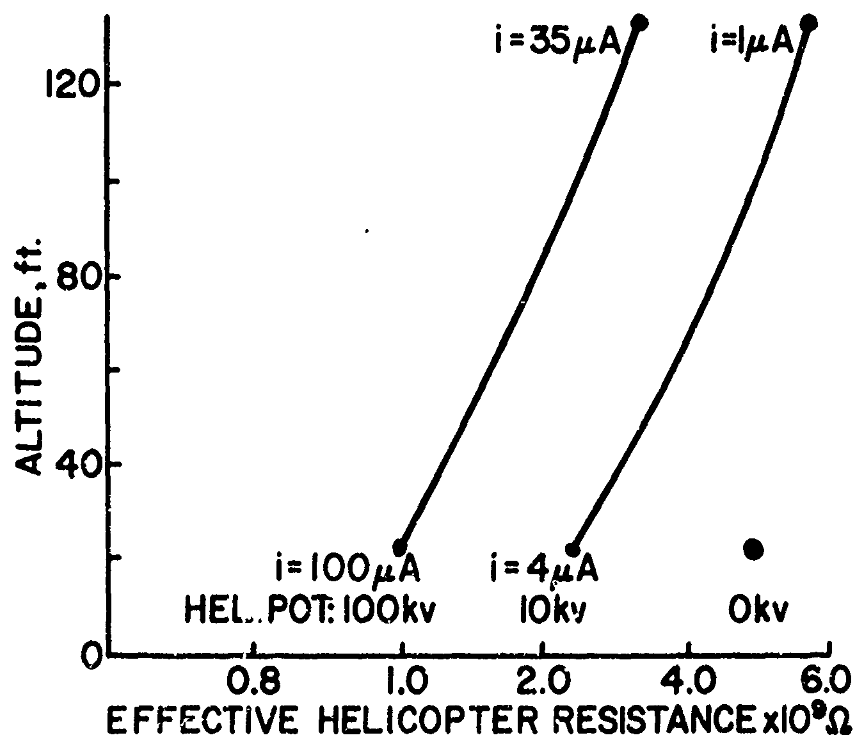
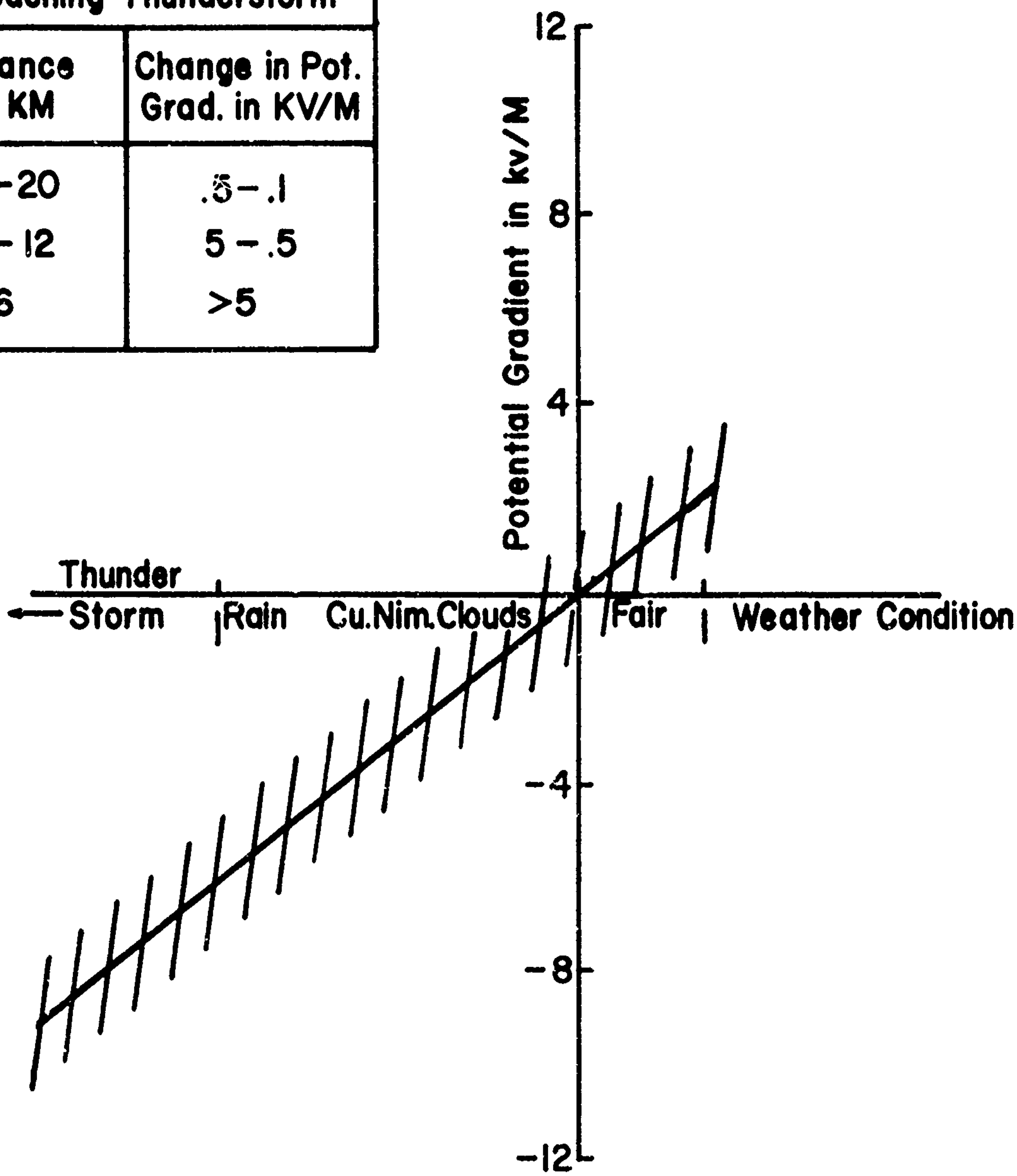


FIGURE 2. MEASURED EFFECTIVE HELICOPTER RESISTANCE vs. ALTITUDE (CH47)

Approaching Thunderstorm	
Distance in KM	Change in Pot. Grad. in KV/M
12–20	.5–.1
6–12	5–.5
<6	>5



MEASURED POTENTIAL GRADIENT IN KV/M NEAR GROUND LEVEL AS A FUNCTION OF WEATHER CONDITION

FIGURE 3.

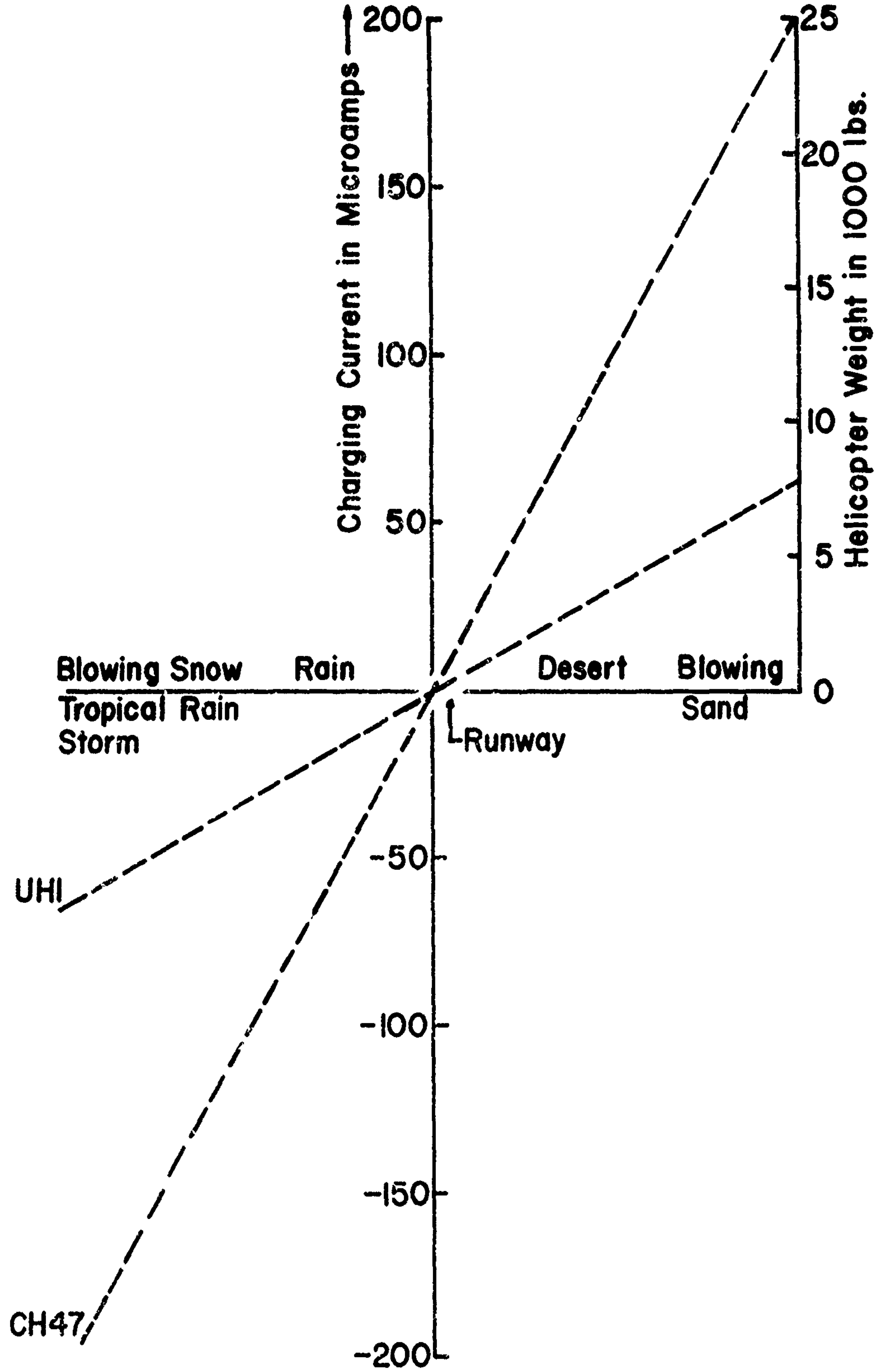


FIGURE 4. ESTIMATED CHARGING CURRENT AS A FUNCTION OF ENVIRONMENT AND HELICOPTER WEIGHT

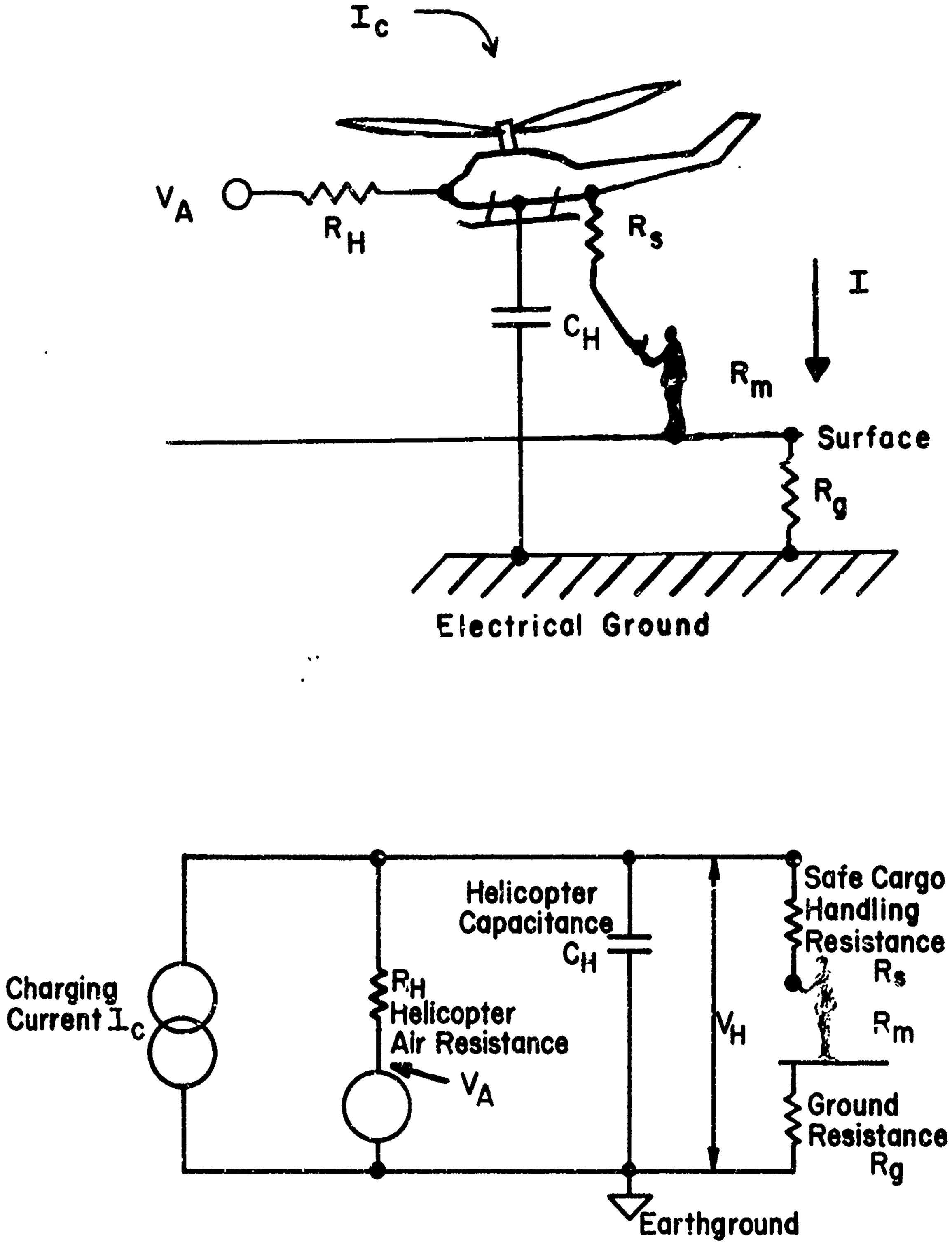
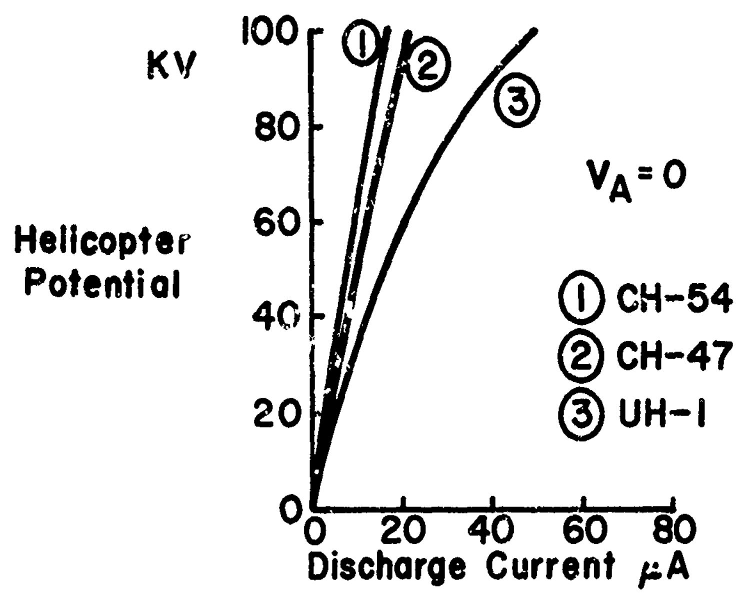
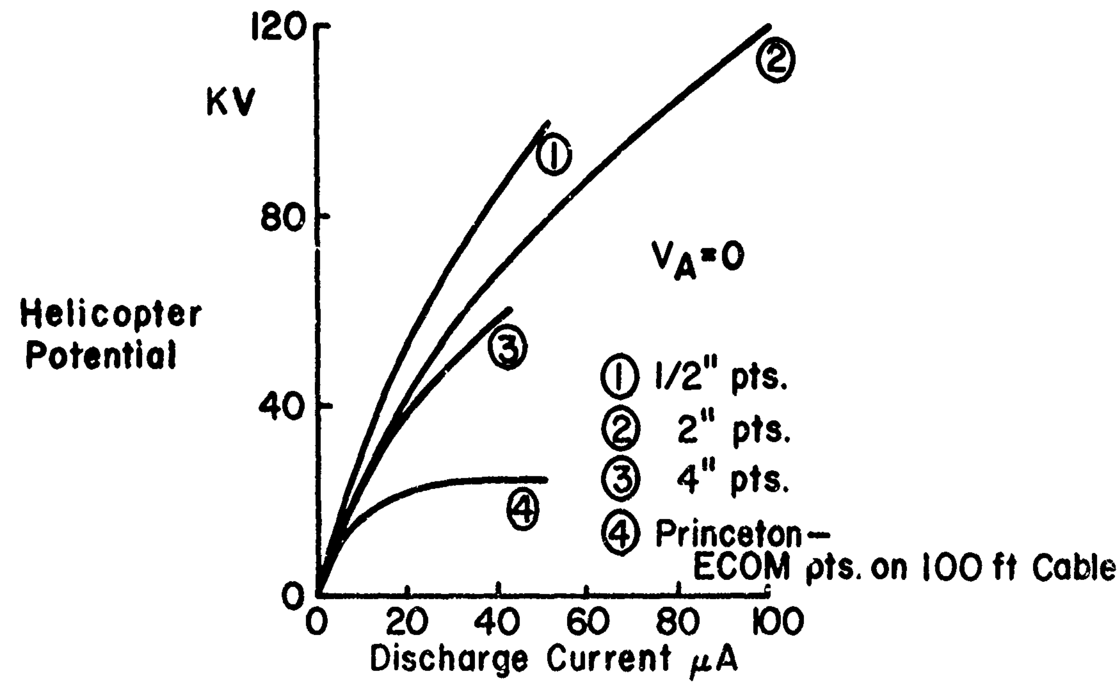


FIGURE 5. CHARGING AND DISCHARGING PROCESSES OF A HOVERING HELICOPTER



HELICOPTER DISCHARGE CURRENT AS A FUNCTION OF HELICOPTER POTENTIAL NATURAL CONDITIONS AT 25 FEET HOVER ALTITUDE

FIGURE 6.



PASSIVE DISCHARGE SYSTEM

FIGURE 7.

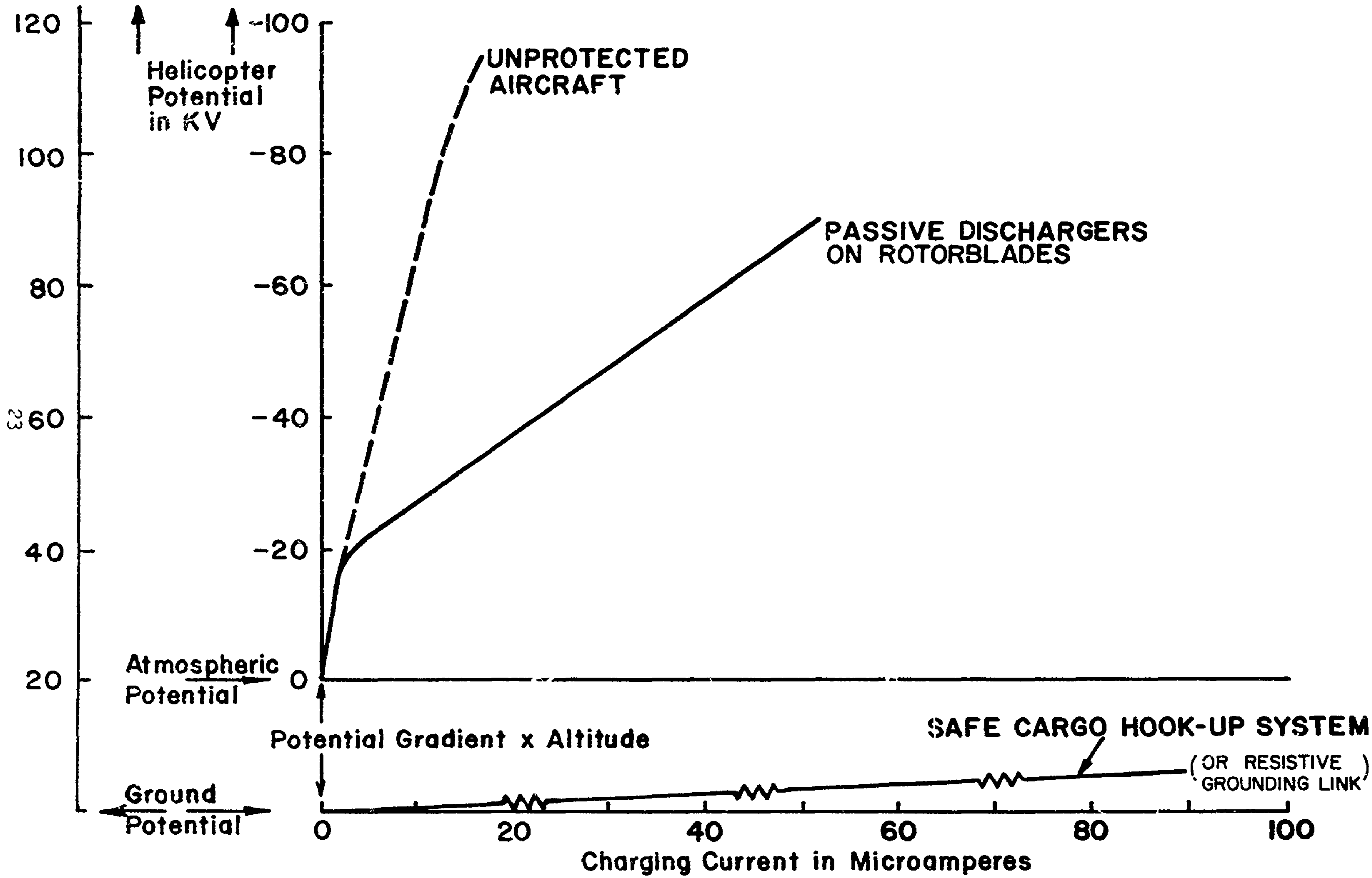


FIGURE 8. SAFE CARGO HOOK UP SYSTEM EVALUATION

APPENDIX 1. FUNDAMENTAL ASPECTS OF CORONA DISCHARGES

1. Introduction

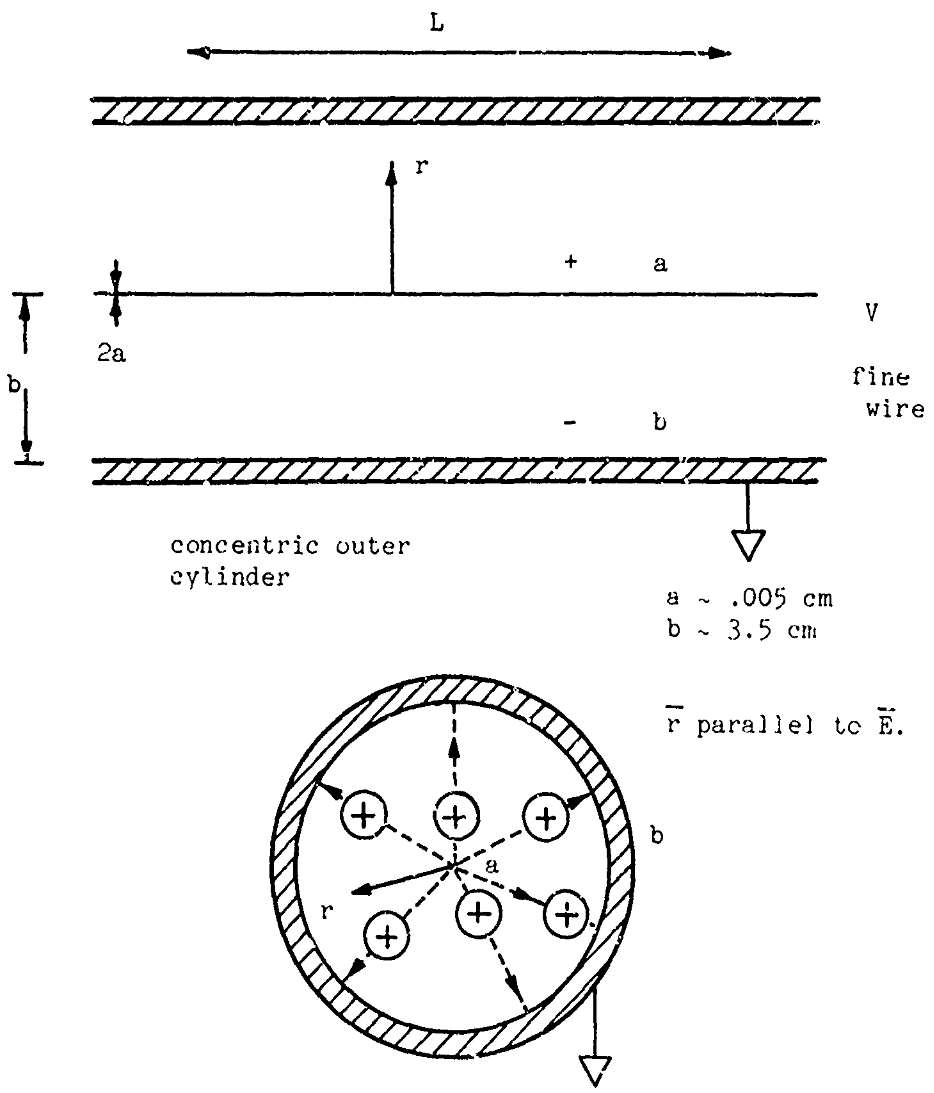
When the potential difference between two electrodes in air is large enough, a spark may be seen. The gas has broken down and become a conductor. The voltage at which the breakdown occurs is a function of the gas, the state of the gas, the geometry of the electrodes, the electrode materials, the state of the electrodes, and the nature of the power supply applying the voltage. If the voltage is decreased once spark has started and if one of the electrodes has sharply curved surfaces (i.e. a needle or fine wire) eventually the spark disappears, but a low current is still carried through the gas. A typical voltage might be several kilovolts and a typical current several microamps. This is the current of the corona discharge.

The corona is a self-sustained discharge because the charge carriers are not created with the aid of some outside source (such as high energy radiation). It is an incomplete failure of the gap. This failure occurs in a tiny region near the small radius of curvature, while the rest of the gap carries a "dark" current. This means that the field is high only near the highly stressed electrode which has the large curvature and it is only in this field that the gas can be ionized. The dark current will be shown to be ions created in this high field region. The ions are transported in a low field at a low velocity.

If one electrode is a thin wire, and is positively charged, the corona will appear as a thin light blue sheath covering the wire surface. The blue light is indicative of high energy radiation emitted in the positive corona. If the wire is negatively charged corona appears as reddish tufts of glowing gas, at points along the wire. The radiation will be shown not to be crucial to the negative corona process.

Corona in air can occur between concentric cylinders, the classical coaxial geometry. This geometry is very convenient for investigation of the corona phenomena, as it provides a good experimental configuration and a easier calculations than most other geometries. This geometry is shown in Illustration A1-1, typical numbers used in this study are $a = 1x10^{-4}m$, $b = 7x10^{-2}m$.

Corona takes place in the thin sheath surrounding the wire where the glow can be observed. The polarity of the voltage determines the color of the glow. For wires of diameter greater than .075 mm in air, positive corona appears at lower voltage than negative corona, whereas for smaller wires the reverse is true (Reference A1-1). Each polarity must be considered separately since the mechanisms are not exactly the same.



Coaxial Geometry, illustrating the Radial Field of Coaxial Corona Discharge

Illustration A1-1

2. Negative Corona Process (coaxial geometry)

a. Description of the corona process

The potential of the wire is negative, and is increased with respect to the environment; the electrostatic field near the surface of the thin wire electrode is increased.

Natural ionization, by cosmic rays and terrestial radioactivity, produces about twenty ion-electron pairs per cubic centimeter which accumulate in time. The steady state level is of the order of two thousand pairs per cubic centimeter (Reference A1-2). These natural ions and electrons are under the influence of the large fields formed by the superposition of the individual fields of each of the many electrons on the wire surface. All positive ions will be attracted to the surface and with a drift velocity, related to the field vector. Eventually the ions will reach the wire surface. Any nearby electron in the metal will have to choose between its attraction to the positive ion and its attraction to the wire surface. For ions in air the ion attraction potential is higher than the work function of the metals by a factor of two or three. The electron will drop into the lower energy level provided by the ion with energy to spare. The energy difference must be absorbed by the surrounding particles in the form of kinetic energy, internal energy, or radiation. One possibility is that the energy can be used to free yet another electron from the metal. This freed electron will then be repelled by the wire field and reach very high energies between collisions. The condition for this to occur is stated as,

$$\varepsilon_i \geq 2 \cdot \phi \qquad \text{A1-1}$$

That is, the ionization potential, ε_i of the ion must be at least as large as twice the work function of the metal, Φ. Work functions are usually about four or five electron volts and ionization potentials less than fifteen or sixteen electron volts.

The positive ions give rise to the emission of electrons from the wire. These electrons together with the initial triggering electrons are accelerated to high energies away from the wire surface. They collide primarily with the neutral gas molecules around them. The ionization and excitation (inelastic) cross sections for the electron-molecule collision at these energies has been well tabulated and are found to be very large. The electrons will ionize the gas quite readily. The ionization reaction is of the form,

$$e^- + N_2 \rightarrow 2e^- + N_2^+ \qquad \text{A1-2}$$

Since the electron created can ionize as well, and since each electron can ionize many times, there is an exponential rise in electron and positive ion numbers and a similar rise in current. This rise is the electron avalanche in a gas, first studied in detail by Townsend fifty years ago. The avalanche does not continue indefinitely because the field decreases after a short distance from the wire surface. The electrostatic field of the coaxial wire as a function of radius for a given voltage difference, V, is,

$$\vec{E}(r) = \frac{V}{r \ln \frac{b}{a}} \left(\vec{e}_r \right) \qquad \text{A1-3}$$

$\vec{E}$ is the field in the radial direction.
V is the applied voltage.
r is radius.
b is outer cylinder radius.
a is wire radius.
e_r is the unit vector in the radial direction.
r_c is the critical radius; $r_c = r\ (\alpha = \eta)$

The coaxial geometry is shown in Illustration A1-1, the electrostatic field of equation A1-3 is plotted in Illustration A1-2, using the

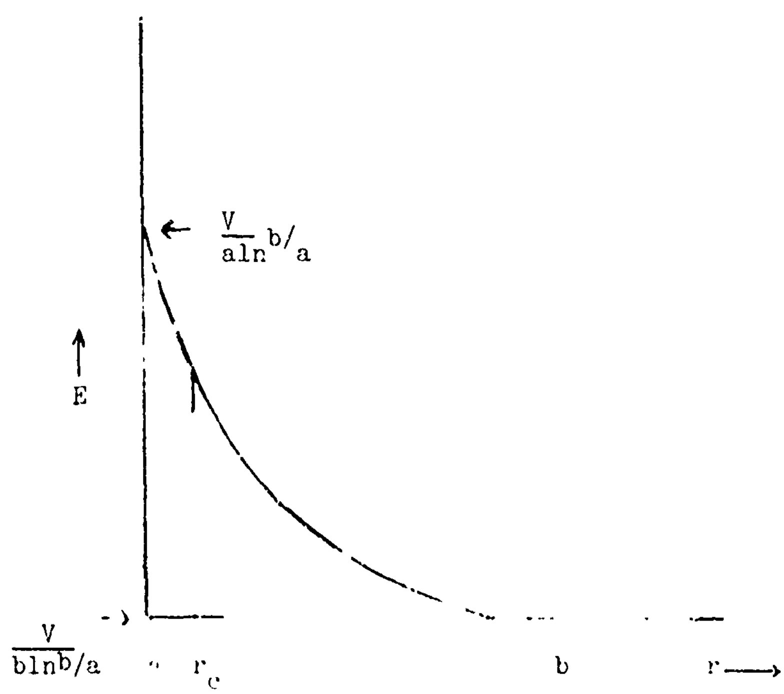


Illustration A1- 2

data as shown below:

$V = 5$ Kilovolts
$b = 3.5$ cm
$a = .038$ mm
$E(a) = 200$ kV/cm
$E(r_c) = 20$ kV/cm
$E(b) = .2$ kV/cm
$r_c = 10 \cdot a$

Some of these numbers will be distorted significantly when the discharge begins since the current carriers themselves contribute a "space charge" field.

When electronegative gases are present, there is another important process, the electron attachment. In air oxygen is the most abundant electronegative gas, with an energy of formation of 2.2 ev. The attachment reaction is of the form:

$$e^- + O_2 \rightarrow O_2^- + (2.2 \text{ ev}) \qquad \text{A1-4}$$

which may or may not require a third body to carry off the excess energy.

At higher energies, another reaction, the dissociative attachment, can remove electrons from the gas. The excess energy of the electron can dissociate the molecule, AB by a reaction of the form

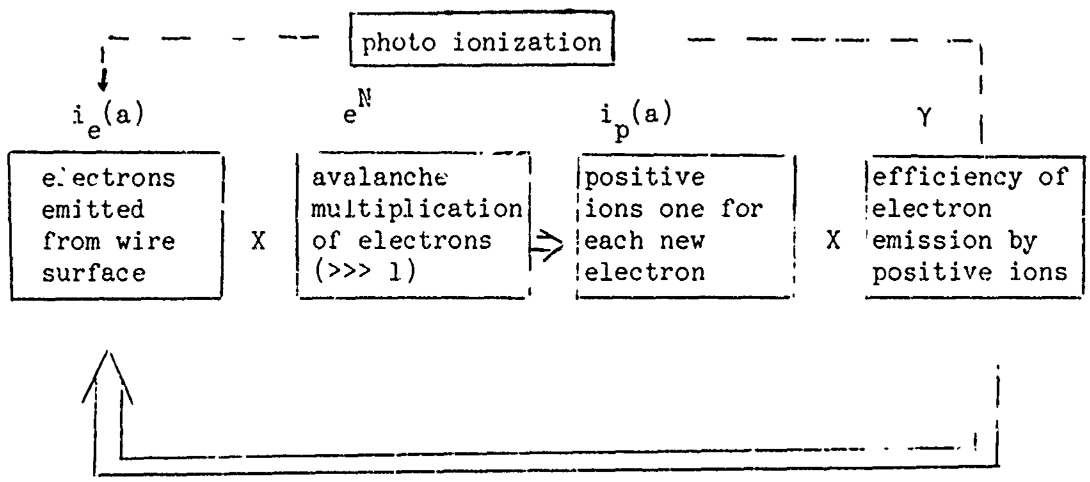
$$AB + \tilde{e}^- \rightarrow A + B^- \qquad \text{A1-5}$$

where either both A and B are electronegative or B is electronegative. Also an electron can be produced if the negative ion energy rises, and the attached electron is detached by a collision:

$$\tilde{O}_2^- + N_2 \rightarrow O_2 + N + e^- \qquad \text{A1-6}$$

b. Block diagram of the negative corona process

In negative corona, the natural electrons in air trigger an avalanche in the large field near the negative wire surface. The few electrons available at small radii multiply exponentially and create positive ions, more electrons, and excited molecules. Postive ions move to the wire surface where they become neutralized. Since the ionization potential of the gas molecules is more than twice the electrode metal work function, there is sufficient surplus energy from the neutralization to emit free electrons from the metal. The radiation emitted from deexcited molecules sustains some level of photoelectric electron emission from the wire surface. The electrons emitted by these two mechanisms are in the best position to multiply by avalanche. Once the threshold field in this region is reached, the cycle begins and current rises until it is constrained by the power supply. If **gamma** is the fraction of the ions which liberate electrons, a block diagram of the negative corona process can be made as shown in illustration A1-3.



$$i_e(a) \times e^N = i_p(a) + i_e(b)$$

$$i_p(a) \times \gamma = i_e(a)$$

Illustration A1-3 (Reference A1, A4, A5)

For the example in this study typical currents are of the order of two microamps per cm of wire length and voltages are between five and ten kilovolts. Wire diameters are about 10^{-4} meter and cylinder diameters about 7×10^{-2} meter. Threshold is of the order of five kilovolts. With the data given in the literature it is possible to calculate the relative contribution to current of each carrier as a function of radius. i_p/i_1 is positive ion relative current. i_n/i_1 is negative ion current. i_e/i is electron current. α is the first Townsend coefficient and η is the electron attachment coefficient. The basic avalanche relation is

$$di_e = \left[\alpha(x)-\eta(x)\right] i_e(x)dx \qquad \text{A1-7}$$

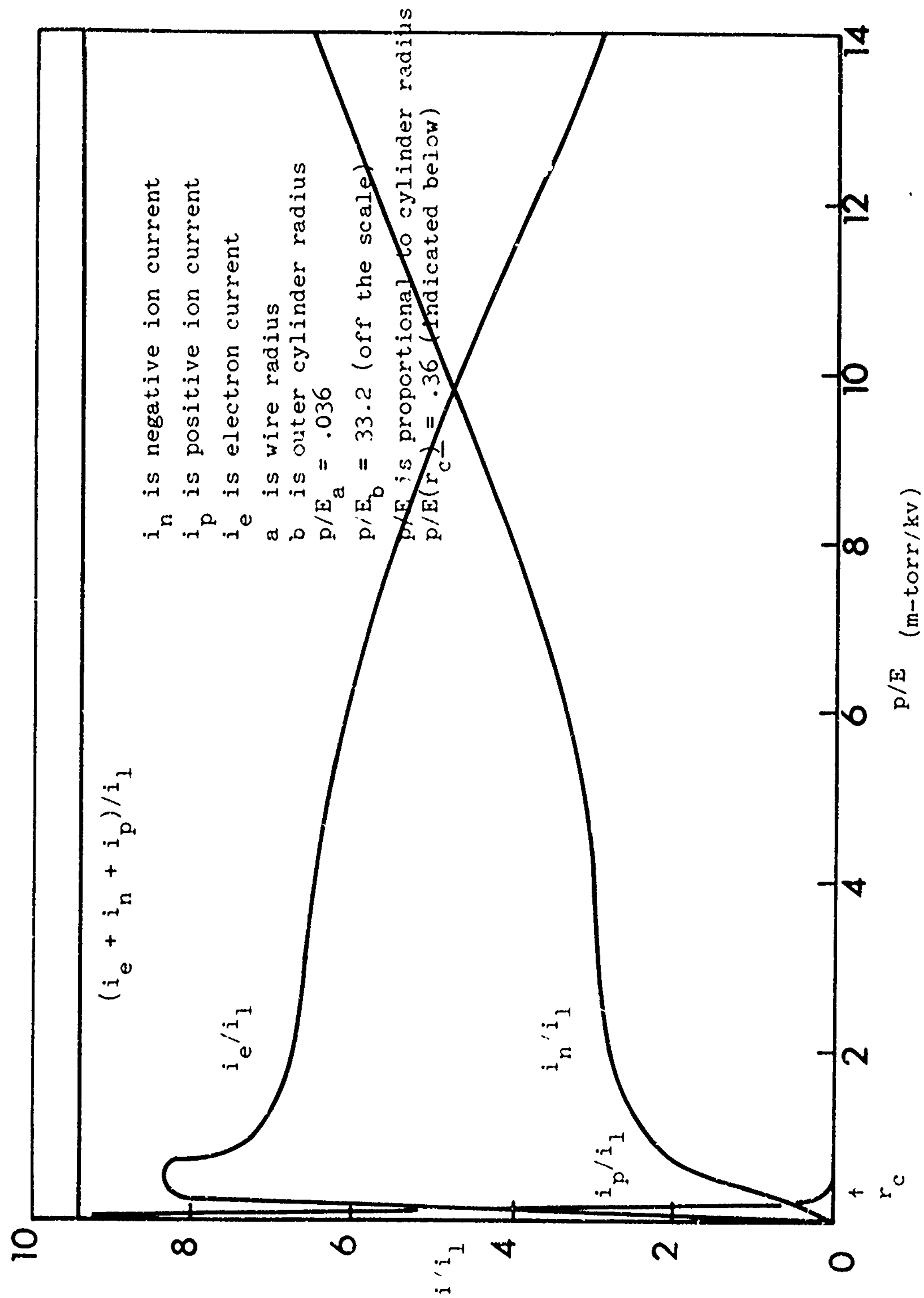
x is the distance of travel. α and η are measured in air as a function of reduced field, E/p, and field is known as a function of x. If only the electrode field is used, the currents are calculated from the following formulas,

$$i_n = \int_{\frac{p}{E_a}}^{\frac{p}{E}} aE_a \; i_e\left(\frac{p}{E}\right) \frac{\eta}{p} \, d\left(\frac{p}{E}\right) \qquad \text{A1-8}$$

$$i_p = \int_{\frac{p}{E}}^{\frac{p}{E_b}} aE_a \; i \left(\frac{p}{E}\right) \frac{\alpha}{p} \, d\left(\frac{p}{E}\right) \qquad \text{A1-9}$$

$$i_e\left(\frac{p}{E}\right) = i_e(a) \exp \left[\int_{\frac{p}{E_a}}^{\frac{p}{E}} \left(\frac{\alpha-\eta}{p}\right) aE_a \, d\left(\frac{p}{E}\right) \right] \qquad \text{A1-10}$$

Only relative currents are calculated so $i_e(a)$ need not be known. α is wire radius and b is outer cylinder radius. Currents are graphed in illustration A1- 4. There is some inaccuracy in the calculation for this polarity because the charges distort the field at large p/E. For qualitative description, it is satisfactory.



Relative Current as a Function of Inverse Reduced Field in Negative Corona Between Coaxial Cylinders.

Illustration A1-4

3. Positive Corona Process (coaxial geometry)

a. Description of the corona process

When the wire is positively charged it repels the positive ions, and attracts the electrons and negative ions. When the potential of the wire is increased, the electrostatic field near the surface of the thin wire electrode, is increased. The field is very high near the wire surface and drops off quickly as radius increases. Any stray electron in the vicinity of the wire will accelerate towards the wire. If the electron does not become attached to some electronegative molecule, it will ionize the gas by the avalanche process. If it becomes attached, the negative ion which is formed will move toward the wire. Eventually when E/p becomes greater than nine kilovolts/meter-torr at small radii, the electron will detach and contribute an insignificant amount to the electron current which has been created there by avalanche (Reference A-10). The positive ions created in the avalanche process will move to higher radii and lower fields and carry the corona current to the larger "collector" cylinder to radius b. The electrons attach as they move through the low fields between "b" and r_c in positive corona. If the current emitted from b was i_e (b), then the current at r_c would be approximately,

$$i_e (r_c) \doteq e^{-5.1} i_e (b) \doteq (.0061) i_e (b) \qquad \text{A1-11}$$

There must therefore become other means by which secondary electrons are supplied to the vicinity of r_c. Since this new means of secondary electron production is as effective as that of its counterpart in negative corona, why does it not appear for both polarities? The only other way electrons can be provided at r_c to sustain the discharge is by photoionization of the gas. Another reaction which takes place in the avalanche process is the excitation of neutral particles by high energy electrons. After the "trigger" electrons initiate the first avalanche, many of the molecules are excited. The electron excitation of a molecule is written.

$$\tilde{e}^- + N_2 \rightarrow N_2^* + e^- \qquad \text{A1-12}$$

This excitation potential may be as high as the ionization potential of other species of molecules in the gas, such as oxygen. The excited molecule later emits a photon.

$$N_2^* \rightarrow N_2 + \;^{\nearrow} \qquad \text{A1-13}$$

The excitation and ionization are very similar. The energy for ionization is close to the excitation energy. The probability of excitation will be larger or smaller than the probability of ionization when the number of electrons which can excite is bigger or smaller than the number which can ionize. The cross section for ionization

in much larger than the cross section for photoionization, hence the ionization is therefore much more frequent than the excitation. The cross section for each of the two processes have a larger but similar electron energy dependence.

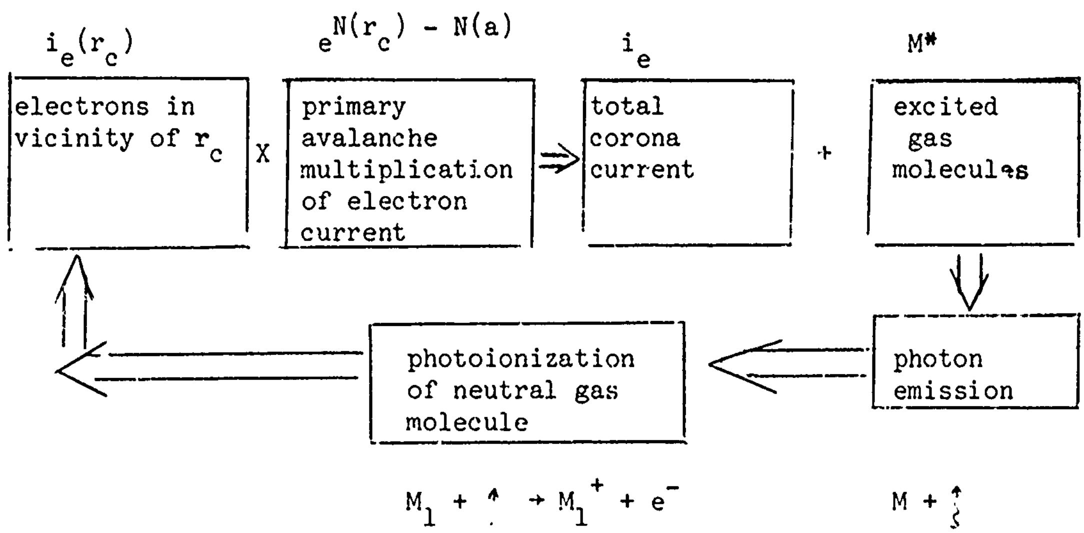
The ultra-violet photons emitted may ionize molecules of ionization potential lower than that of the molecules that emitted them. The photoionization reaction can be written as:

$$+ O_2 \rightarrow O_2^{+} + e^{-} \qquad \text{A1-14}$$

Since the photons are neutral particles, they may photoionize at radii larger than the radius where they are emitted. They will be emitted for the most part where ionization is highest, at "a", and will be absorbed within a short distance of "a". A certain number of them will photoionization between "a" and some larger radius greater than r_c. These secondary electrons then multiply by avalanche.

Block diagram of the positive corona process

In the positive corona almost all ionization and attachment take place at very small radii where the field is almost all electrode field. In positive corona the electron avalanche is directed toward the wire surface. It is only below the critical radius, r_c, where electrons can multiply. Between r_c and a, electron current rises much faster than



i_e (r near r_c) X $e^{N(r_c) - N(r)} = i_e(a)$ + excited molecules

excited molecules emit photons

photoionization creates i_e (r near r_a)

Illustration A1-5 (Reference A3, A4, A5)

an exponential, so it is a good approximation that all secondary electrons which initiate avalanche originate at r_c or in its immediate vicinity. Secondary electrons are created by photoionization of neutral molecules. It is known that excited nitrogen emits photons of energy high enough to ionize oxygen and other components of air which have ionization potentials less than that of nitrogen. It is only with multi-component gases that this mechanism appears, block diagram of the positive corona process can be made and is shown in illustration A1-5.

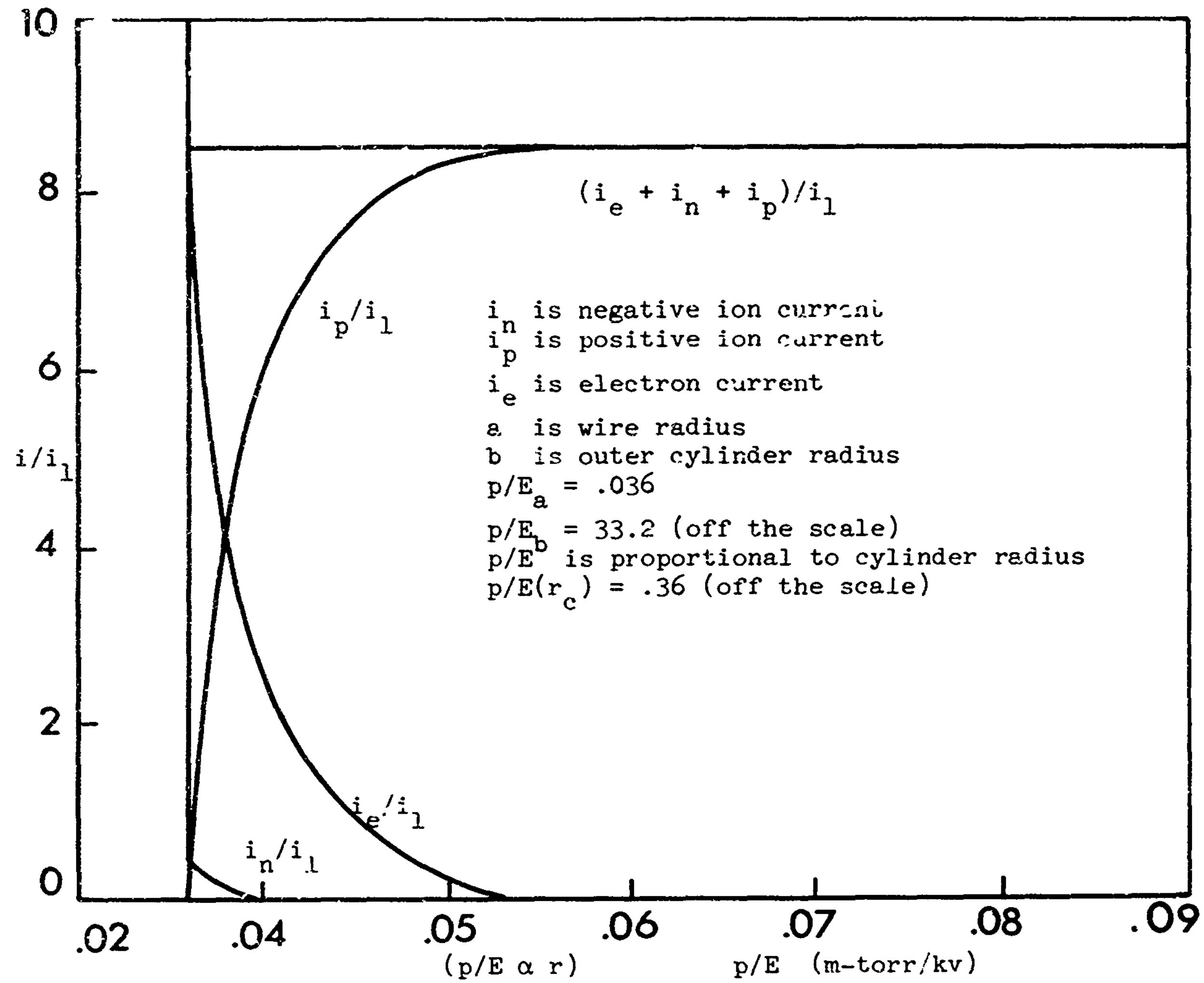
The formulas used to calculate the relative currents are given for the same geometry described on the preceeding pages.

$$i_n = \int_{\frac{p}{E}}^{\frac{p}{E_b}} aE_a \; i_e \left(\frac{p}{E}\right) \frac{\eta}{p} \, d\left(\frac{p}{E}\right) \qquad \text{A1-15}$$

$$i_p = \int_{\frac{p}{E_a}}^{\frac{p}{E}} aE_a \; i_e \left(\frac{p}{E}\right) \frac{\alpha}{p} \, d\left(\frac{p}{E}\right) \qquad \text{A1-16}$$

$$i_e \left(\frac{p}{E}\right) = i_e(a) \exp \left[\int_{\frac{p}{E}}^{\frac{p}{E}_{crit}} \left(\frac{\alpha-\eta}{p}\right) aE_a \, d\left(\frac{p}{E}\right) \right] \qquad \text{A1-17}$$

Relative current curves for positive corona are given in illustration A1-8. These curves do not have the inaccuracy of the negative corona curves because avalanche moves toward the wire and all ionization and attachment take place near the wire. Calculations similar to these are made by Heymann for wires of larger diameter (Reference A1-1). Data for α and η were taken from References A4, 5, 6, 10, 11 and 12.



Relative Current as a Function of Inverse Reduced Field in Positive Corona Between Coaxial Cylinders.

Illustration A1-6

4. Comparison of negative and positive corona processes

In illustration A1-3 and A1-5, the graphs for the electrical currents were made for the coaxial geometry described in the proceeding pages. Extensive measurements of the distribution of potential in a corona tube is given in reference A1-14.

As shown, the positive corona and negative corona currents have little in common. The positive corona current is carried by electrons at the wire surface and by positive ions at larger radii. The critical radius r_c is of the same order as the inner radius a. The current is carried exclusively by positive ions between $r_c/15$ and outer radius b. This is a range which is approximately $99\frac{14}{15}\%$ of (b-a). The positive corona is confined because the avalanche proceeds towards the wire surface.

Avalanche in negative corona moves away from the wire. The many electrons formed between a and r_c are attached only very slowly since attachment rates are everywhere much lower than the ionization rates at higher fields. The current at large radii is eventually carried by negative ions alone but this occurs only approximately at a radius equal to .67 (b-a). The current is carried in equal amounts by negative ion and electron at a radius approximately equal to .33 (b-a). In negative corona process the attachment at larger radii will depend somewhat on the space charge fields. The error using the electrostatic field formula will be less because the charge density of electron carriers is some orders of magnitude smaller than that of ions carrying the same current.

These corona processes described above are of interest in understanding the current generating mechanisms. It appears that at distance "far" away from the corona, the current is determined by the ion current. In different geometrical configurations, the same mechanisms of the corona process occurs. The influence of the proximity of corona points on corona current was investigated.

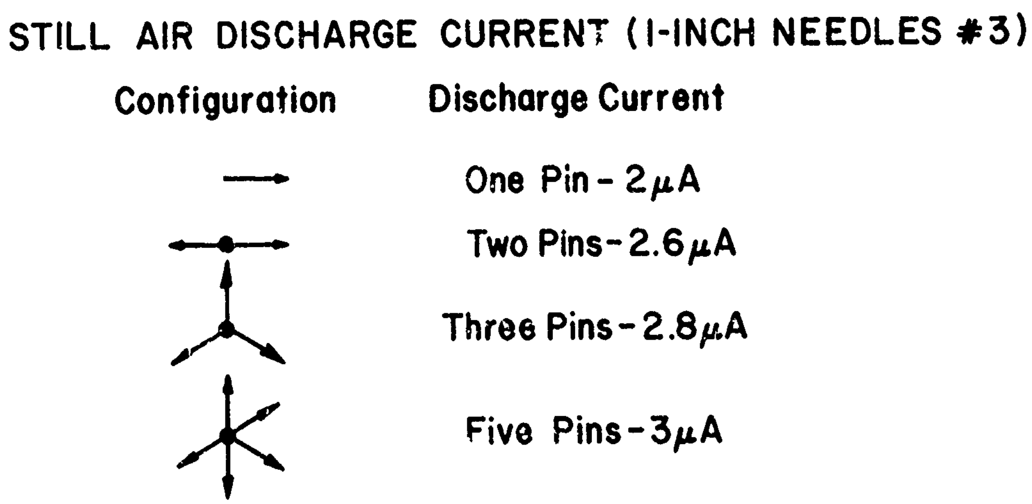
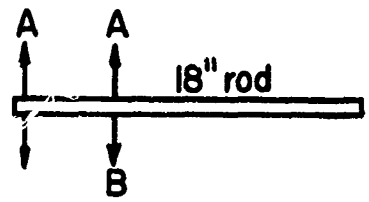


Illustration A1-6

The configurations constructed with sewing needles no. 3, is shown in illustration A1-6, the gap length is about 5 feet and 20 kilo Volts is applied to the needle configurations and the magnitude of the outgoing corona currents are shown in illustration A1-5.

The proximity influence of corona points on a rod/or blade were tested by the configuration shown in illustration A1-7, using sewing needles no. 3. For a constant applied voltage of 20 kV and a gap length of about 5 feet, the values of the outgoing corona currents are shown in the illustration A1-7.



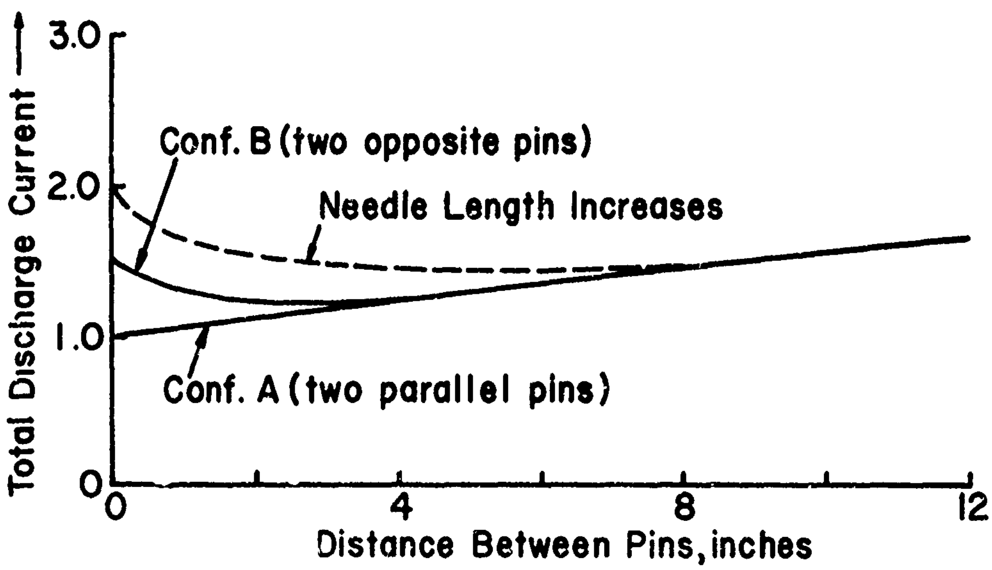


Illustration A1-7

5. Ion Mobility

In the coaxial configuration, it is possible to define an ion mobility at all radii except in a region very near the fine wire surface where the field becomes too high. Mobility, μ, is the ratio of ion drift velocity, $\bar{v}_d$, to electric field, $\bar{E}$.

$$\bar{v}_d = \mu \bar{E} \qquad \text{A1-18}$$

When gas velocity is zero, the ions follow the vector field lines. When the field is very large like the field near the wire surface, mobility depends on field. The approximation is made that this high field region is small enough to ignore mobility variation with field. Because other corona electrode geometries have similar electrostatic fields, μ can be assumed independent of field in most configurations. The low field mibility, μ, can be described by : (reference A1-16).

$$\mu = \frac{C}{n_1 \sqrt{\alpha_1} \sqrt{\frac{m_2}{m_1} (m_2 + m_1)}} \qquad \text{A1-19}$$

C = constant.

α_1 = polarizability of the neutral gas.

n_1 = number density of gas molecules.

m_2 = mass of ion.

μ is approximately 1.9 cm^2/volt-sec in the corona discharge in air. Mobility data and discussions of mobility derivations are given in reference A1-16.

In order to calculate ion speed, the field must be known. Field is derived from the divergence equation:

$$\nabla \cdot \bar{E} = \rho_{c/\varepsilon_o} \qquad \text{A1-20}$$

ρ_c is charge density.

ε_o is a constant.

From a charge conservation relation, charge density is related to ion drift speed and current density.

$$\bar{J} = \rho_c \bar{v}_d \qquad \text{A1-21}$$

The solution of the equations A1-17, 19 and 20 for an infinitely long fine wire concentric with a large outer cylinder becomes: (reference A1-17).

$$E(r) = \left\{ \frac{i/_L}{2\pi\epsilon_o\mu} + \left(\frac{V_o}{r \ln b/a} \right)^2 \right\}^{1/2} ; a < r < b \; ; a << b \qquad \text{A1-22}$$

E is radial field between cylinders.

V_o is corona threshold voltage of the positive center wire.

$\frac{V_o}{r\ln(b/a)}$ is threshold field as a function of radius.

i/L is current per unit wire length.

Coaxial corona fields in air were measured experimentally in reference A1-18. From a curve fit of this formula to his data average ion mobility is estimated to be 1.9 cm^2/volt-sec. Numbers given in the literature are within approximately 20% of 1.9.

A similar equation is erived for a concentric spheres model.

$$E(r) = \left\{ \frac{i}{6\pi\epsilon_o\mu r} + \left(\frac{V_o a}{r^2} \right)^2 \right\}^{1/2} ; \; a < r < b \; ; \; a << b \qquad \text{A1-23}$$

a is inner sphere radius.

b is outer sphere radius.

i is total current.

V_o is threshold voltage.

Equation A1-22 is approximated by equation A1-24 at low r, r ~ a

$$E(r) \doteq \frac{V_o}{r\ln(b/a)} \; ; \; r \sim a \qquad \text{A1-24}$$

At large r, r ~ b, it is approximated by equation A1-25 if i/L and b are not too small.

$$E(r) = \left\{ \frac{i/L}{2\pi\epsilon_o\mu} \right\}^{1/2} ; \; r \sim b \qquad \text{A1-25}$$

Equation A1-23 is approximated by A1-26 at low r, r ~ a, and by A1-27 at large r, r ~ b, if i and b are not too small.

$$E(r) \doteq \frac{V_o a}{r^2} \quad ; \quad r \sim a \qquad \text{A1-26}$$

$$E(r) \doteq \frac{i}{6\pi\varepsilon_0\mu r}^{1/2} \quad ; \quad r \sim b \qquad \text{A1-27}$$

A new variable appears in equations A1-22 and A1-23 which has not been discussed; this is V_o, the voltage measured when current is decreased to zero. The dependence of V_o on parameters which determine gas state, gas composition, and electrode construction is difficult to derive. V_o depends on the efficiency of the various corona mechanisms described in reference A1-16.

6. Discharge Parameter Relationships

a. Electric Field of the Corona Discharge

1. With the approximation that the high field region is small enouch to ignore mobility variation with the field, the field can be derived from the following equations:

$$\nabla \cdot \underline{E} = \rho_o/\varepsilon_o \qquad \text{A1-20}$$

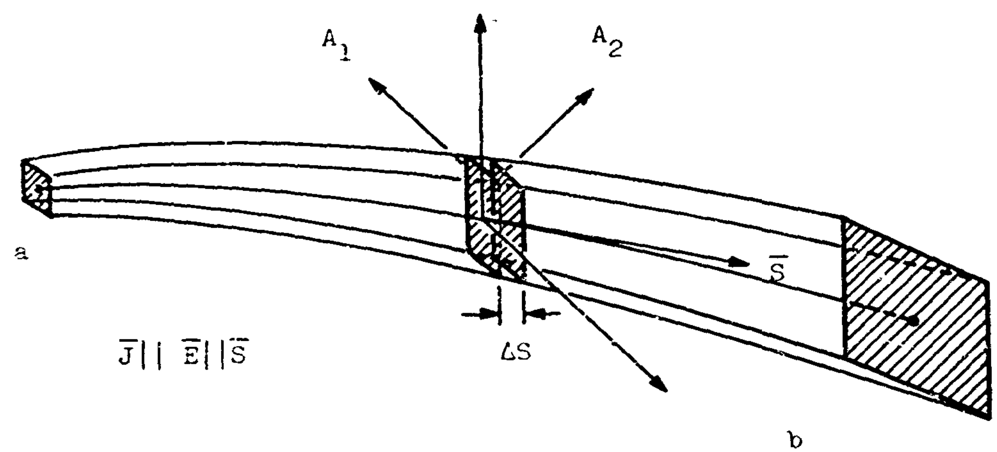
$$\bar{J} = \rho_c \bar{v}_d \qquad \text{A1-21}$$

$$\bar{v}_d = \mu\bar{E} \qquad \text{A1-18}$$

$$\nabla \cdot \underline{E} = \frac{J}{\varepsilon_o \mu E} \qquad \text{A1-28}$$

$$E\bar{\nabla} \cdot \underline{E} = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-29}$$

Every corona beam is composed of tubes of current flux. It is possible to find the form of the solution in a tube of flux of narrow cross section. The narrow tube follows a path, and cross section is a function of position on the path. Path displacement is the vector $\bar{s}$. A section of a tube is drawn in Illustration A1-7.



A Tube of [illegible] with Cross Sectional Area, A(s), and Path, s, Between a at the Positive Source and b at Ground.

Illustration A1-7

Current flows parallel to $\bar{s}$ and normal to the tube cross section. This tube is sectioned at A_1 and A_2, the areas normal to flow of ion current. All other surfaces are parallel to current and field so that current in a tube is constant.

The above equation is rewritten with the divergence defined,

$$E \cdot \lim_{\Delta V \to oA} \int \frac{\bar{E} \cdot \bar{n}}{\Delta V} \, dA = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-29}$$

ΔV is the volume of tube section and A is its surface area. $\bar{n}$ is the unit vector normal to the surface. The area integral contributions are made on A_1 and A_2 only, since all other surfaces have normals normal to flow and field. If E_1 and E_2 are the values of field at those surfaces,

$$E \cdot \lim_{\Delta V \to o} \left(\frac{E_2 A_2 - E_1 A_1}{\Delta V} \right) = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-30}$$

Letting ΔV approach zero as Δs approaches zero and letting A_1 remain constant, E_2 is approximated by,

$$E_2 = E_1 + \left(\frac{dE_1}{ds} \right)_1 \Delta s \qquad \text{A1-31}$$

Upon substitution,

$$E \cdot \lim_{\Delta s \to o} \left(\frac{(E_1 + \frac{dE_1}{ds} \Delta s)\, A_2 - E_1 A_1}{\Delta V} \right) = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-32}$$

$$E \cdot \lim_{\Delta s \to o} \left(\frac{\frac{dE_1}{ds} \Delta s A_2 + E_1 (A_2 - A_1)}{A_1 \, \Delta s} \right) = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-33}$$

$$E \left(\frac{dE}{ds} + \frac{E}{A} \frac{dA}{ds}\right) = \frac{J}{\varepsilon_o \mu} \qquad \text{A1-34}$$

$$E \, (AdE + EdA) = \frac{ids}{\varepsilon_o \mu} \qquad \text{A1-35}$$

$$AE \; d(AE) = \frac{iA(s)ds}{\varepsilon_o \mu} \qquad \text{A1-36}$$

$$(AE)^2 = \frac{2i}{\mu\varepsilon_o} \int_a^s A(s^1)ds^1 + (A(a)E(a))^2 \qquad \text{A1-37}$$

s' is a dummy variable. $\overline{A}$, an average tube cross section area, is defined.

$$\overline{A} \equiv \frac{\int_a^s A(s')ds'}{\int_a^s ds'} = \frac{1}{s-a} \int_a^s A(s')ds' \qquad \text{A1-38}$$

Substitute A1-38 into A1-37

$$(AE)^2 = \frac{2i}{\mu\varepsilon_o} \overline{A} \cdot (s-a) + (A(a)E(a))^2 \qquad \text{A1-39}$$

Solve for E.

$$E(s) = \left\{ \frac{ai\overline{A}}{\mu\varepsilon_o A^2} (s-a) + \frac{E^2(a)A^2(a)}{A^2(s)} \right\}^{1/2} \qquad \text{A1-40}$$

Each tube is defined for different values of i by its cross section of area A(a) on the surface of the source. As total current in the ion beam is changed, the current, i, in the tube originating from the source surface area, A(a), also changes. A(s) for s not equal to a depends on i and μ. $\overline{A}(s)$ and E(a) may also depend on i and μ. When total discharge current approaches zero, so also does i approach zero. Equation A1-40 becomes A1-41 where $E_o(s)$ is threshold field and $A_o(s)$ is threshold tube area.

$$\lim_{i \to o} E(s) = \left\{ \frac{E_o^2(a)A(a)^2}{A_o^2(s)} \right\}^{1/2} = \frac{E_o(a)A(a)}{A_o(s)} \equiv E_o(s) \qquad \text{A1-41}$$

$E_o(s)$ is the field of charges on the surfaces of the corona electrodes at threshold. It is the nature of corona discharges to have the largest field near the sharp source, $s \to a$, and E(s) is approximated well by equation A1-41

$$E(s) \doteq \left\{ \frac{E(a)A(a)}{A(s)} \right\}; \quad s \doteq a \qquad \text{A1-42}$$

When s is near a, the field is due primarily to charges on the source surface. It follows that the second term in brackets in equation A1-40 is a contribution to E(s) from the charges on the electrode surface. No matter what the value of i, in order that the discharge continue, field near the source must be greater than or equal to its threshold value.

$$E(a) \geq E_o(a) \qquad \text{A1-43}$$

From inspection of A1-39,

$$E(a) \leq \frac{A(s)}{A(a)} E(s) \qquad \text{A1-44}$$

Combining A1-43 and A1-44 gives A1-45

$$E_o(a) \leq E(a) < \frac{A(s)}{A(a)} E(s) \qquad \text{A1-45}$$

When current is flowing the discharge is constrained by the power supply. E(a) has that value which minimizes the energy stored in the electric field without violating the constraints. Stored energy is the sum of the volume integral of the flux tubes.

$$\text{Energy} = \sum_j \int_{a_j}^{b_j} \frac{1}{2} \varepsilon_o E^2(s_j) A(s_j) ds_j \qquad \text{A1-46}$$

If a constant current power supply is used, it is easy to show that energy is minimized when E_a is a minimum.

$$E(a) = E_o(a) \qquad \text{A1-47}$$

Curve fits of V(r) with experimental data taken from reference A1-14 verify this conclusion for the coaxial cylinder geometry. Equation A1-40 may be rewritten.

$$F(s) = \left\{ \frac{ai\bar{A}}{\mu\varepsilon_o A^2} (s-a) + \frac{E_o^2(a)A^2(a)}{A^2(s)} \right\}^{1/2} \qquad \text{A1-48}$$

Voltage is obtained from an integral of the field along the path of the tube.

$$V(s) = \int_s^b E(s')ds' \qquad \text{A1-49}$$

Threshold voltage is obtained from A1-49 when i is zero. $E_o(s)$ is defined in A1-41 above.

$$V_o(a) = \int_a^b E_o(s')ds' \qquad \text{A1-50}$$

$$V_o(a) = \int_a^b \frac{E_o(a)A(a)}{A_o(s')} ds' \qquad \text{A1-51}$$

$$E_o(a) = V_o(a) \Big/ \int_a^b \frac{A(a)}{A_o(s')} ds' \qquad \text{A1-52}$$

Equation A1-52 is substituted into A1-48.

$$E(s) = \left\{ \frac{ai\bar{A}}{\mu\varepsilon_o A^2} (s-a) + V_o{}^2(a) \frac{A^2(a)/A^2(s)}{\left[\int_a^b A(a)/_{A_o(s')} ds'\right]^2} \right\}^{1/2} \qquad \text{A1-53}$$

$$E(s) = \left\{ \frac{2i\bar{A}}{\mu\varepsilon_o A^2} (s-a) + \frac{V_o^2(a)}{A^2(s)\left[\int_a^b \frac{1}{A_o(s')} ds'\right]^2} \right\}^{1/2} \qquad \text{A1-54}$$

It is not till s >> a that the first term in the brackets contributes significantly to field so the first term may be simplified, and A1-54 is rewritten.

$$E(s) = \left\{ \frac{2i\bar{A}}{\mu\varepsilon_o A^2} s + \frac{V_o^2(a)}{A^2(s)\left[\int_a^b \frac{1}{A_o(s')} ds'\right]^2} \right\}^{1/2} \qquad \text{A1-55}$$

This relation simplifies for the two-dimensional coaxial wire configuration of infinite length drawn in illustration A1-7. This geometry consists of a single radial tube of area per unit length, A/L, where A/L is given by A1-56.

$$A/L = 2\pi r = A_o/L \qquad \text{A1-56}$$

$$\bar{A}/L = \frac{1}{r}\int_a^r 2\pi r dr \doteq \pi r \qquad \text{A1-57}$$

$$E(r) = \left\{\frac{i/L}{2\pi\varepsilon_o\mu} + \frac{V_0^2}{r^2/n^2(b/a)}\right\}^{1/2} \qquad \text{A1-58}$$

The two parameters in equation A1-55 which depend directly on the gas state and composition are mobility and threshold voltage. Mobility is described by equation A1-18 above. A change in environment influences the field by changing mobility and threshold.

b. Threshold

A difficult parameter to derive analytically as a function of gas and geometry is the threshold voltage V_o. The relations found experimentally (reference A1-19) for parallel wires and for two spheres can be written as

$$V_o = V_o(\rho_o)\frac{\sqrt{\delta}\,(1 + \frac{C}{\sqrt{R\delta}})}{(1 + \frac{C}{\sqrt{R}}}\sqrt{\delta} \qquad \text{A1-59}$$

where $V(\rho_o)$, C, and R depend on geometrical parameters. R is radius. When $C/(R^o)^{1/2}$ is much greater than 1, V_o is approximated well by relation of the form of A1-60

$$V_o = V(\rho_o)\frac{\rho}{\rho_o} \qquad \text{A1-60}$$

Electrodes such as the fine wire or thin needle fall in this category. As this limit is approached, the threshold field becomes more and more uniform and corona does not appear. At atmospheric pressures only sparks appear. The above relation is a good approximation to Paschen's law for parallel planes with approximately 1 cm. gap (reference A1)

c. i, V, ρ Relationships

Field in a tube of flux has been derived to be

$$E\,(s) = \left\{\frac{2i\,\bar{A}\,(s)}{\mu\varepsilon_o\,A^2\,(s)}\,s + E_o^2\,(s)\right\}^{1/2} \qquad \text{A1-23}$$

$$\mu = \mu_o\,\frac{\rho_o}{\rho}$$

If the source is very small and electrode field drops very quickly as s increases, like the field of a fine wire or thin needle,

$$V_o = V_o(\rho_o)\sqrt{\frac{\rho}{\rho_o}} \qquad \text{A1-60}$$

$$E_o\,(s) = E_o\,(s,\,\rho_o)\sqrt{\frac{\rho}{\rho_o}} \qquad \text{A1-61}$$

Substituting A1-62 into A1-23 and as the Voltage is the line integral along the tube path between the electrodes one can write:

$$V = \sqrt{\frac{\rho}{\rho_o}}\int_a^b \left\{\frac{2i\,\bar{A}}{\mu_o\varepsilon_o\,A^2}\,s + E_o^2\,(s,\,\rho_o)\right\}^{1/2} ds \qquad \text{A1-62}$$

If A is insensitive to density changes then

$$(V)_i = V\,(\rho_o)\sqrt{\frac{\rho}{\rho_o}} \qquad \text{A1-63}$$

In order to know how V depends on density it must be known how A depends on density. Assume that the current is constant and current densities are high. There are two effects on A(s) due to a change in mobility. A higher mobility allows faster beam spreading. An increased mobility also means that beam charge density is decreased, so repulsion forces are weaker. These two effects are equal and opposite in the tube described above. Tube area depends on mobility and current only because the initial conditions depend on mobility and current. The conditions when repulsion first dominates beam spreading at low s depend on these parameters. Experiments with corona beams verify the square-root-of-density relation derived above. Tube area is therefore insensitive to density changes. Since the choice of tube was arbitrary, all tubes have areas insensitive to density. Since the beam is a superposition of the tubes, the current distribution in a beam cross-section must be insensitive to density changes at constant current.

If current is small enough the field expression may be expanded in a series with only two terms. Integration is simplified and the following expression is derived.

$$i = \frac{k\rho_o}{\rho} V_o (V-V_o) \qquad \text{A1-64}$$

If current is large enough then

$$i = \frac{k_1\rho_o}{\rho} V^2 \qquad \text{A1-65}$$

Current-voltage curves can be described by a relation of the form,

$$i = \frac{k\rho_o}{\rho} V (V-V_o) \qquad \text{A1-66}$$

which has both asymptotes described (A1-2, A1-5, A1-19, A1-20, A1-21). The expression requires that if threshold has a square root density dependence, so must voltage at constant current.

d. Mobility and airflow

The factor k in the current voltage relationship of equation A1-66 is directly proportional to the ion mobility (equation A1-63). When an airflow is present, the ion velocity is equal to the vector sum of the drift velocity of the electrical field and airflow.

Corona current with wind along the corona point. Corona current:

$$\begin{aligned} i &= k_1(v + w)(V - V_o) \qquad \text{A1-67} \\ &= k_1 v(V - V_o)(1 + \frac{w}{v}) \end{aligned}$$

where V is the applied voltage at the corona point (volts)

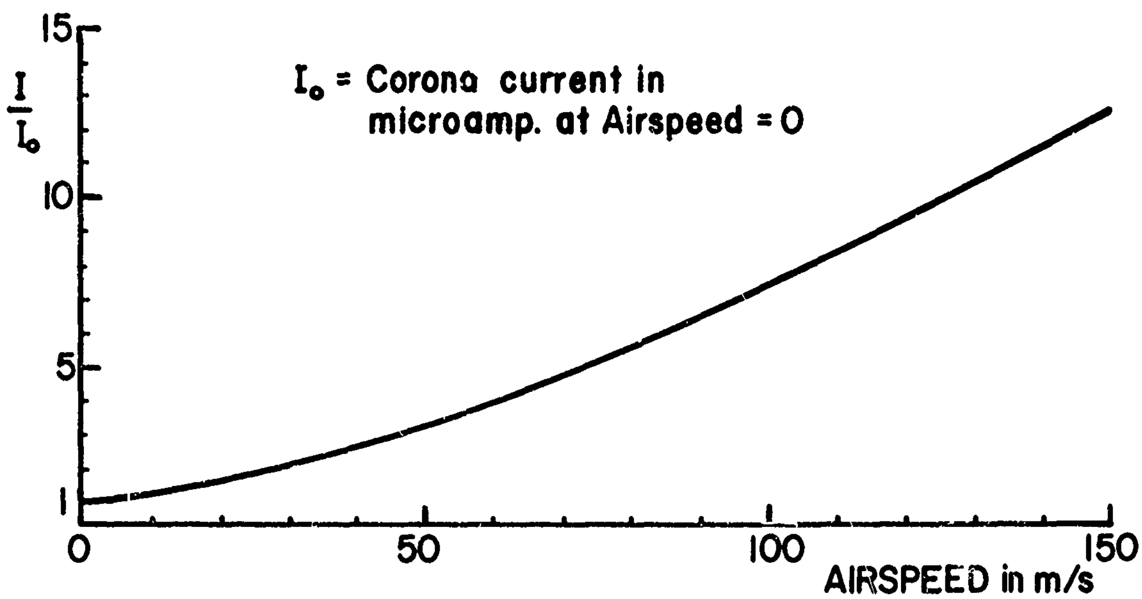
V_o is the corona starting potential (volts)
k_1 is a constant; $k_1 v = k$ in equation A1-67.
v is the velocity of the ions (meters/second)
w is the wind velocity (meters/second)

The corona current with wind influence can be summarized as follows. For a corona point, the derived results for still air remain valid and can be applied in the case where a wind is blowing along the corona point, if the result is multiplied by a factor $(1 + \frac{w}{k_1 \mu V})$ or $(1 + \frac{w}{v})$

where w is the wind (meters/second)

k_1 is the constant
μ is the ion mobility (m/s/volts/m)
V is the potential of the point (volts) or effective voltage (volts)

The large effect of airflow is shown in illustration A1-8.



CORONA CURRENT AS A FUNCTION OF AIRSPEED

Illustration A1-8

e. Corona and impurities

There is no model for corona which applies to all gases. The simplest example of corona in another gas is the positive corona in pure nitrogen. A more detailed discussion is given in references (A-2, A-5). The positive corona mechanism for secondary electron generation in air requires that oxygen or some equivalent be present. (references A-2, A-4, A-5). This mechanism is replaced by a glow discharge in pure nitrogen in which both the anode and cathode phenomena characteristic of the glow are observed. The negative corona did not depend on the oxygen-nitrogen combination. Its mechanisms in nitrogen are the same as in air. It follows that the positive corona characteristics in pure N_2 are sensitive to the addition of traces of oxygen. In air the coronas are relatively insensitive to small amounts of most foreign gases, especially since air contains a variety of gases already.

Gas	Mole Fraction
N_2	78.09%
O_2	20.95%
A	00.93%
CO_2	00.03%
Ne	1.8×10^{-3}%
He	5.24×10^{-4}%

The state and composition of air in the atmosphere are variables. Water vapor is the most abundant impurity. Vapor pressure fluctuates rapidly between zero and approximately twenty torr. An impurity such as water will change gas mobility and corona threshold.

1. Mobility and impurities

In order to see the effects of water on the mobility, some calculations and assumptions are made which give typical results. A primary assumption is that the functional dependence of the mobility on gas mass, ion mass, polarizability, density, and electric field is correct. A second assumption is that charge exchange will occur whenever the reaction energy is positive and will not occur when it is negative provided the collision frequency between the exchanging species is high. The fraction of the positive ions created from each species in the avalanche ionization is assumed to be equal to the fraction of neutrals of that species originally in the gas. O_2^+ and N_2^+ are assumed to be the only ions produced in the electron avalanche. (Many other ions are formed (reference A-22)).

a. Target particle change

The above assumptions are now exploited. Charge exchange between positive ions and neutrals of like species decreases mobilities. It is ignored here although there is evidence of symmetry exchange for nitrogen ions in nitrogen gas at higher fields. (references A-5, A-23). It is the polarizability of the gas through which the ion is traveling which determines the size of the coefficient of the inverse fifth power force law. This coefficient is also charge-dependent, but it can be shown that this mobility as derived is independent of charge cancels the larger crossection obtained because of increased interaction forces. The ions are singly charged in the corona.

The following reaction is suggested,

$$N_2^+ + O_2 \rightarrow O_2^+ + N_2 + 3.4 \text{ ev} \qquad \text{A1-68}$$

An energy imbalance of 3 ev is not too large to hinder the reaction. Since the collision frequency is high, the carriers in dry air exygen ions. Oxygen does not exchange with added water molecules. The reaction energy is mildly negative.

$$O_2^+ + H_2O \rightarrow O_2 + H_2O^+ - .4 \text{ ev} \qquad \text{A1-69}$$

The water receives charge from the nitrogen in an amount comparable to that received by the oxygen when each is weighted by its density. The water exchanges quite readily with the oxygen since the energy balance is approximate and favors the reverse reaction.

$$H_2O^+ + O_2 \rightarrow H_2O + O_2^+ + .4 \text{ ev} \qquad \text{A1-70}$$

The collision frequency of the water with an oxygen or nitrogen ion is comparable to the collision frequency of these ions with nitrogen or oxygen neutrals since the relative velocity at collision is the thermal velocity of neutrals in the gas.

Water changes the mobility of the average ion if no charge exchange takes place. An ion (1) of mobility $k^{(1)}$ in gas (1) and $k^{(1)}_{(2)}$ in gas (2) in a mixture of density $N + N_{(1)} + N_{(2)}$ has a mobility $k^{(1)}_{(1)(2)}$ as given by Blanc's law (reference A1-5). $f_{(1)}$ and $f_{(2)}$ are the mole fractions $N_{(1)}/N$ and $N_{(2)}/N$ respectively. Let $N_{(1)}$ be the air number density of a representative air molecule, and $N_{(2)}$ be the density of water molecules.

$$\frac{1}{k^{(1)}_{(1)(2)}} = \frac{f_{(1)}}{k^{(1)}_{(1)}} + \frac{f_{(2)}}{k^{(1)}_{(2)}} \qquad \text{A1-71}$$

$$\frac{1}{k^{(1)}_{(1)(2)}} = \frac{1}{N} \quad \frac{N_{(1)}}{k^{(1)}_{(1)}} + \frac{N_{(2)}}{k^{(1)}_{(2)}} \qquad \text{A1-72}$$

At a humidity of 100%, the vapor pressure is about 20 torr.

$$f_{(2)} = \frac{20H}{760} = \frac{H}{38} \qquad \text{A1-73}$$

$$f_{(1)} = \frac{760 - 20H}{760} \qquad \text{A1-74}$$

$$\frac{1}{k^{(1)}_{(1)(2)}} = \frac{1}{760} \quad \frac{20H}{k^{(1)}_{(2)}} + \frac{760 - 20H}{k^{(1)}_{(2)}} \qquad \text{A1-75}$$

Since the polarizability of H_2O

$$\frac{\alpha_{H_2O}}{\alpha_{N_2}} = 3.8 \qquad \text{A1-76}$$

$$\frac{\alpha_{H_2O}}{\alpha_{O_2}} = 3.5 \qquad \text{A1-77}$$

$$\frac{k^{N_2^+}_{H_2O}}{k^{N_2^+}_{air}} = .6 \qquad \text{A1-78}$$

$$\frac{1}{k^{N_2^+}_{air\ H_2O}} = \frac{1.02}{k^{N_2^+}_{air}} \qquad \text{A1-79}$$

$$k^{O_2^+}_{air\ H_2O} = .98k^{N_2^+}_{air} \qquad \text{A1-80}$$

Any ion of comparable mass such as NO^+ or N_2^+ has a predicted mobility at saturation approximately .98 of the mobility in dry air. The larger polarizability of the water and its lower mass decrease the ion mobility.

b. Carrier change

Water ions would be expected to have a mobility,

$$\frac{k_{air}^{H_2O^+}}{k_{air}^{O_2^+}} = 1.5 \qquad \text{A1-81}$$

$$k_{air}^{H_2O^+} = 2.28 \qquad \text{A1-82}$$

This is not very different from the estimation for air in the corona, 1.9. A few water ions do not exert much influence on the average mobility. The polarizability is 3.5 times that of the oxygen, and water appears in amounts of the order of 20H. Its ionization potential is only slightly greater than that of O_2. The collision frequency of N_2^+ with O_2 must be compared to that with H_2O.

$$\frac{\nu_{O_2}^{N_2^+}}{\nu_{H_2O}^{N_2^+}} = \frac{p_{O_2} Q_{O_2}^{N_2^+} v_{therm\ O_2}}{p_{H_2O} Q_{H_2O}^{N_2^+} v_{therm\ H_2O}} \qquad \text{A1-83}$$

$$\frac{\nu_{H_2O}^{N_2^+}}{\nu_{H_2O}^{N_2^+}} = \frac{3.4}{H} \qquad \text{A1-84}$$

If H is a maximum, H = 1.

$$\nu_{O_2}^{N_2^+} = 3.4\,\nu_{H_2O}^{N_2^+} \qquad \text{A1-85}$$

If 20% of the original positive avalanche ions are oxygen and 80% are nitrogen and if i_p such ions are created per second,

$$\text{avalanche } i_{O_2^+} = .2\ i_p \qquad \text{A1-86}$$

$$\text{avalanche } i_{N_2^+} = .8\ i_p \qquad \text{A1-87}$$

If water is present at a pressure of 20H (torr),

$$\text{avalanche } i_{H_2O^+} = \frac{H}{38}\ i_p \qquad \text{A1-88}$$

If all N_2^+ ions exchange with either the water or oxygen and since

$$\nu_{O_2}^{N_2^+} = 3.4\ \nu_{H_2O}^{N_2^+} \qquad \text{A1-89}$$

final densities of water and oxygen ions may be calculated. It is assumed that the probability for exchange at each collision is the same for water and oxygen. The final currents of oxygen and water ions are,

$$\text{final } i_{O_2^+} = .2\ ip + \frac{3.4}{1 + 3.4} (.8)\ i_p \qquad \text{A1-90}$$

$$\text{final } i_{H_2O^+} = \frac{H}{38}\ ip + \frac{1}{4.4} (.8)\ i_p \qquad \text{A1-91}$$

$$\text{final } i_{O_2^+} = .82\ i_p \qquad \text{A1-92}$$

$$\text{final } i_{H_2O^+} = .18\ i_p \qquad \text{A1-93}$$

$$\frac{N_{O_2^+}}{N_{H_2O^+}} = \frac{i_{O_2^+}}{i_{H_2O^+}} \cdot \frac{k_{H_2O^+}}{k_{O_2^+}} = \frac{.82}{.18}\ \frac{2.28}{1.50} = 6.9 \qquad \text{A1-94}$$

$$N_{O_2^+} = .87\ (N_{O_2^+} + N_{H_2O^+}) = .87 N_+ \qquad \text{A1-95}$$

$$N_{H_2O^+} = .13 N_+ \qquad \text{A1-96}$$

The oxygen would carry .82 of the total current and average mobility may be found.

$$i_a = N_a\ k_a\ E\ e\ A \qquad \text{A1-97}$$

$$i_b = N_b\ k_b\ E\ e\ A \qquad \text{A1-98}$$

$$k_{ab}\ (N_a + N_b)\ Eea = i_a + i_b \qquad \text{A1-99}$$

$$k^- = k_{ab} = \frac{N_a}{N} k_a + \frac{N_b}{N}\ k_b \qquad \text{A1-100}$$

$$k^- = .13\ k_{H_2O^+} + .87\ k_{O_2^+} \qquad \text{A1-101}$$

$$k^- = .13\ (2.28) + .87\ (1.5) = 1.6 \qquad \text{A1-102}$$

If no water were present then the mobility would be 1.5. The water has raised the average mobility 6.7%. If H_2O^+ exchanges charge with O_2 then the change could be smaller.

Exchange with carbon dioxide (.03% of air) is small because its density is much smaller than that of oxygen or water and because its ionization potential is higher than that of oxygen or water. The same conclusion is made for the other components of air.

2. Threshold and water vapor

Ionization and attachment coefficients in humid air have been measured and compared with the coefficients in dry air. In this report it is stated that the attachment in humid air seems to be a partial pressure weighting of the coefficients of attachment in water vapor and dry air each measured separately.

In both positive and negative corona, ionization takes place only in a small region near the highly stressed source. In this region both ionization and attachment increase when vapor pressure is raised.

From reference A19: "Over a very large humidity range, tests show humidity has no appreciable effect upon the starting point of visual corona if conductor surface is dry." Also if the surface condition is constant, conductor material has little influence on corona starting point.

3. Charge exchange

If the transit time of the ions between electrodes of the coaxial configuration is of the order of a millisecond the ions age. That is, they undergo some reactions in the gas which change their mobility (references A-3, A-13). For example, a major difficulty in purifying vacuum tubes for charge transport experiments is to guarantee that no mercury (or similar materials) are present (reference A-13). Mercury has a very low ionization potential and a mass much larger than the ions formed in most other gases. If the ions have enough time to collide with Hg, the charge will be transferred to the target particle because it has a much lower ionization potential than that of the ion, i.e., N_2^+ or O_2^+. The mobility of the Hg^+ ion formed in the exchange is much lower.

Transit time estimates for three geometries have been made. Keane measured transit times of the order of one msec in the point corona for large gaps. Calculations made agree with measured times. The coaxial wire and the disc on a coaxial rod both have transit times less than a msec since the transport fields are higher. There is appreciable aging of the ions in the geometry used for impurities present in densities greater than $10^{-6} n_o$. An ion collides once on the average with an impurity of this density when transit time is 10^{-3} second.

4. Clustering

The deviations of mobilities in gaseous mixtures from Blanc's law indicate the formation of complexes (reference A-5). Clustering occurs especially with impurities of high dielectric constant such as water vapor, ammonia, and carbon dioxide (reference A-22).

The force that charges exert on neutral particles is attractive. N_2^+ attracts N_2 and forms N_4^+ in low fields. The charges are attacted to all polarizable matter near them. All conductors and dielectrics attract charges. Dirt, dust, sand, organic material and all other materials found in air attract the ions in the discharge. The ions attach to the impurities to form larger charged particles of very low mobility. A lower average mobility increases gap differential resistance. The impurity could be pollution by combustion, dirt blown by the wind on a dry day or organic matter from nearby vegetation. Liquids are found in air in droplet form. The droplets are often conductors and increase ion and electron attachment. In addition to water, certain oils in droplet form are often present in wind tunnels or near combustion engines. If the density of the impurity is low, then the change in mobility and the changes in attachment and ionization coefficients distort the discharge current-voltage characteristics only a little.

The impurity ions follow the field lines until they deposit on the electrode surfaces. They remain on the surface and are removed by vigorous scrubbing. These particles collect on any surface, insulator or conductor.

7. Corona current discharges from a hovering helicopter

The corona discharge from a helicopter is space charge limited i.e., the electric field, which provides the driving force of the ions, is to a large extend determined by the space charge. The change in total current leaving the helicopter due to a change in the environment is hence determined by the change of corona discharge parameters and the change in the space charge.

The major effects of corona discharge current due to environmental changes are summarized below:

a. The effect of geometry

The magnitudes of the corona current from a point is proportional to the point to ground potential difference squared and is strongly dependent upon geometry and atmospheric conditions. Experiments were done to determine the mutual influence 1 to 4 corona points in proximity to each other. (Appendix 1, section 4)

b. The effect of pressure variation

Theoretical analysis and experiments show that the corona current at constant voltage is inversely proportional to the square root of pressure.

c. The effect of temperature variation

Theoretical analysis and experiments show that the corona current at constant voltage is proportional to the square root of temperature.

d. The effect of impurities

Analytical and experimental years indicate that the main effect of impurities is to change the ion mobility, corona threshold and electrode contamination. For the larger corona currents the change in corona threshold can often be neglected. Depending upon the contaminant, the combination of the two can result in an increase or decrease of the corona current. In general, the effect of increase or decrease in ion mobility is a function (and often proportional) to the relative density of the impurity.

e. The effect of relative humidity variation

Theoretical analysis and experimental results show that corona current (generated by a constant voltage source) decreases when the relative humidity increases. The decrease in corona current is proportional to the increase in relative humidity. For a constant voltage

source and a given change in relative humidity, the percentage change in corona current is not only proportional to the mobility change but also proportional to the corona current size. Typical variations of corona currents versus relative humidity are shown in illustration A1-9.

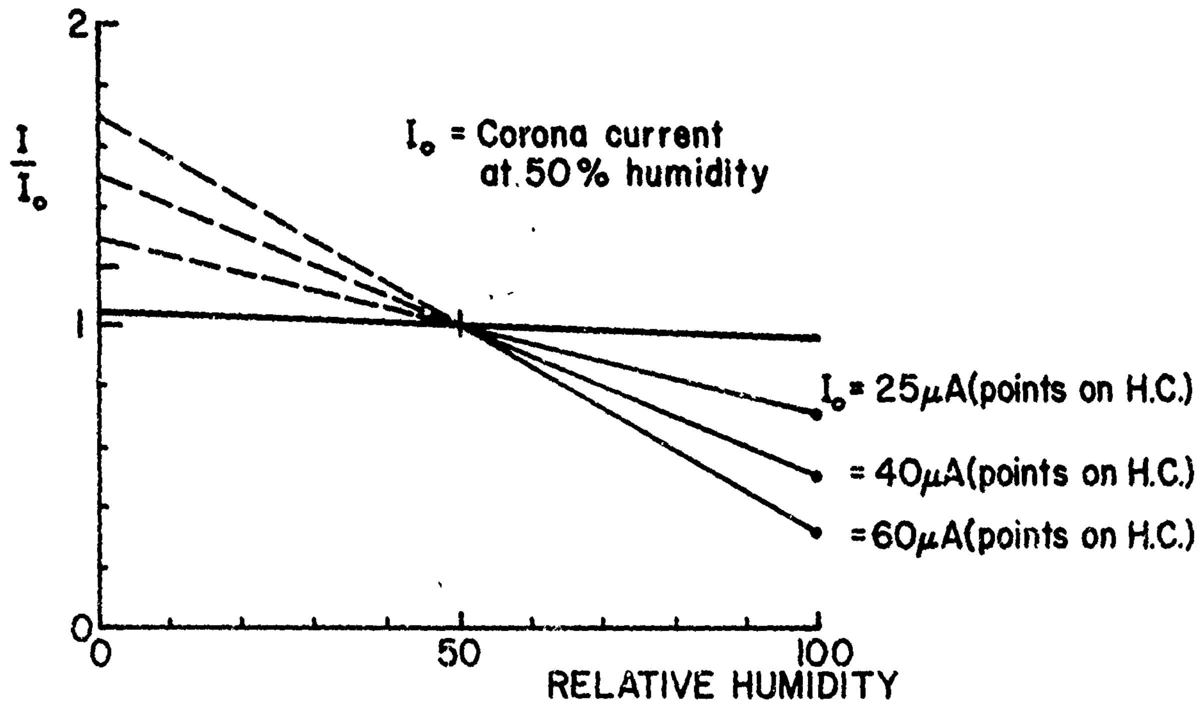


Illustration A1-9

Typical corona current variation as a function of humidity

f. The effect of density variations

The effect of the atmospheric pressure and temperature on the corona current can be combined by relating the pressure and temperature with density. The corona current is inversely proportional to the square root of density,

or

$$I \approx \frac{1}{\sqrt{\frac{\rho}{\rho_o}}}$$

where ρ = density

ρ_o = reference density

and $\rho = \frac{PM}{R^*T} \quad PV = kT$

where ρ = density in kg m^{-3}

P = pressure in N m^{-2} (kg m^{-1} sec^{-2})

T = temperature in ^0k

V = volume m^3

R^* = gas constant

g. Space charge effects

In the theoretical and experimental investigations of corona currents between 1 and 100 microamperes, space charge effects have large influences, for example:

1. Corona current from a sharp point (needles) is space charge limited. As a result, removal of the space charge by blowing air increases the corona current proportional to air velocity.

2. Corona current fro fine wires or discs have relatively large surface areas. After the corona current has started, for a given increase in applied voltage, a much larger increase in corona current is obtained as compared to the sharp point. Also the corona current appears to be less sensitive to air velocity in the region of 0-20 microamperes.

REFERENCE TO APPENDIX A1

A1. Combine, James Dillon, Gaseous Conductors, Dover Publications, Inc. N.Y. 1958.

A2. Loeb, Leonard B., Electrical Coronas, Univ. Calif. Press, Berkeley, L.A., 1965.

A3. Von Engel, A., Ionized Gases, 2nd Ed. Oxford at the Clarendon Press (Fair Lawn, N.J.), 1965.

A4. Heymann, F.G., Corona on Wires in Air, Univ. of Pretoria, Jan., 1965.

A5. Loeb, Leonard B., Basic Processes of Gaseous Electronics, University of California Press Berkeley and Los Angeles, 1955.

A6. Harrison, M.A., and Geballe, R., Simultaneous Measurement of Ionization and Attachment Coefficients, Phys. Rev. 91, 1, 1953.

A7. Kuffel, E., Electron Attachment Coefficients in Oxygen, Dry Air, Humid Air, and Water Vapor, Proc. Phys. Soc., 74, 297, 1959.

A8. Tozer, B.A., R. Thorburn, and J.D. Craggs, The Attachment of Slow Electrons in Air and Oxygen, Proc. Phys. Soc., 72, 1081, 1958.

A9. Robinson, N., Solar Radiation, Elsvier Publishing Co., Amsterdan, London, N.Y., 1966 (Editor) p. 68.

A10. Loeb, L.B., Energy of Formation of Negative Ions in O_2, Phys. Rev. 48. 684 (1935).

A11. Huxley, L.H.G., and A.A. Zaazou, Experimental and Theoretical Studies of the Behavior of Slow Electrons in Air. I., Proc. Roy. Soc. (London), A196, 402, (1949).

A12. Llewellyn-Jones, F., The Glow Discharge, (and an Introduction to Plasma Physics), London: Metuen & Co. Ltd., N.Y.: John Wiley & Sons, Inc.

A13. Loeb, L.B., and A.I. Kip, J. Applied Phys., 10, 142, 1939.

A14. Booth, H.J. Phys. Rev., 10, 266, 1917.

A15. Loeb, Leonard B., The Kinetic Theory of Gases, Dover, N.Y., 1961.

A16. Burke, W. Air Velocity Measurement with the Ion Beam of the Positive Corona Discharge PhD Dissertation, Princeton University (To be Published).

REFERENCE TO APPENDIX A1 Continued

A17. Dodd, Edward E., A Short Method for Evaluation of the Townsend Integral for Electron Avalanche Formation, Phys. Rev., 78, 620, 1950.

A18. Bradbury, Norris E., Electron Attachment and Negative Ion Formation in Oxygen and Oxygen Mixtures, Physical Review, 44, 883, Dec. 1, 1933.

A19. Peek, F.W., Dielectric Phenomena in High Voltage Engineering, McGraw Hill Book Company, Inc., N.Y. 1934.

A20. Chapman, Seville, et al, Electrostatic Field Measurement, Corona Discharge, and Thunderclouds, Cornell Aeronautical Laboratory Report No. CAL 68, Buffalo, N.Y., March, 1956.

A21. Von Engel, Ionized Gases, 2nd Ed. Oxford Clarendon Press, 1965.

A22. Glockler, G. The Electrochemistry of Gases and other Dielectrics John Wiley & Sons Inc., New York, 1939.

A23. Holstein, T. Mobilities of Positive Ions in Their Parent Gases, Phys. Rev. 56 832, 1952.

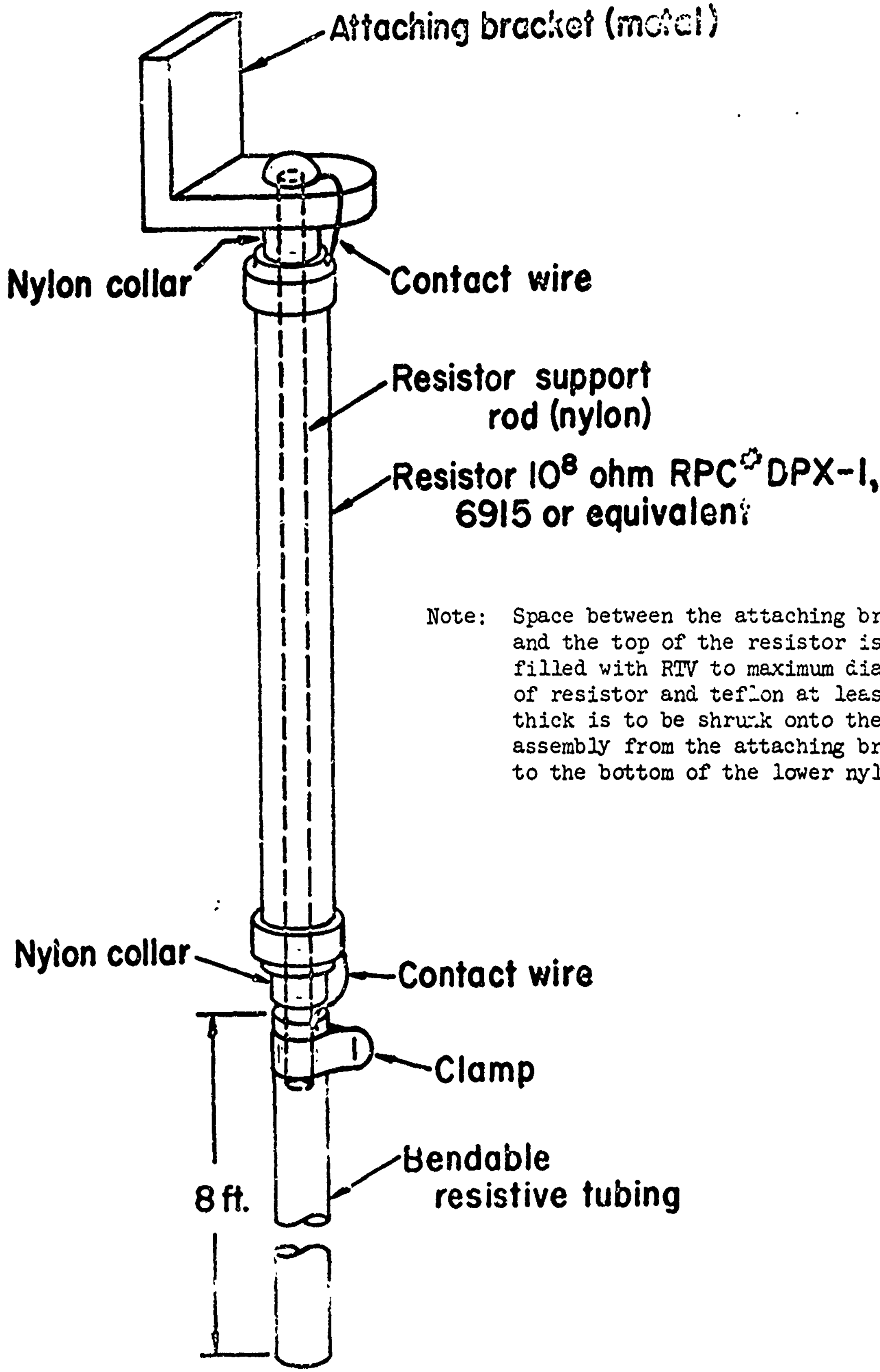
APPENDIX II

Principles of Design of Resistive Link Device

The development of a practical resistive link discharge device was done during this program and was tested in connection with the CH-54 program. These laboratory models were also tested in the ECOM environmental chamber to see whether or not the resistance could be maintained under adverse weather conditions. This test indicated that teflon-coated resistors could maintain their resistance in severe environmental conditions, including rain. Several models of a resistive link were developed for application to Army helicopters. The elements of this resistive link discharger (Illustration A2-1) are as follows:

1. A device for attaching the link to a helicopter.
2. A teflon-covered resistor which has a resistance of 10^8 ohms.
3. A connection from the resistor to a tail piece which consists of conductive rubber tubing of appropriate mechanical characteristics and having a resistance of about one megohm.

After liturature search and preliminary investigations, it appears that a resistive link device can be constructed using conductive plastics (bulk conduction). It is expected that the latter approach would give a simpler construction and a relative inexpensive resistive link device.



Note: Space between the attaching bracket and the top of the resistor is to be filled with RTV to maximum diameter of resistor and teflon at least .020" thick is to be shrunk onto the assembly from the attaching bracket to the bottom of the lower nylon collar.

Resistive Link Discharge Device

Illustration A2-1